Chapter 4
Powertrain

The powertrain includes the engine, in modern cars mostly a reciprocating internal combustion engine, and the gearbox, that converts the engine torque into the torque needed for vehicle traction. Some engines of this type that were developed before the invention of the automobile are first described: The De Rivaz, Barsanti, Lenoir and Otto were important milestones in the development of present spark-ignition engines, sometimes improperly called *Otto engines*. The description will be limited to this family of engines, neglecting, for sake of simplicity, compression-ignition engines, sometimes referred to as *Diesel engines*.

An historical perspective of car spark-ignition engine, developed from the end of the 19th till the end of the twentieth century, will then follow. Dedicated subsections are addressed to the technological evolution of the main auxiliary systems of the spark-ignition engines, such as those for air-fuel mixture preparation, lubrication, ignition and starting.

A major issue in spark-ignition engines and, more in general, in internal combustion engines is their torque characteristic, i.e. the plot of the torque versus the rotation speed.

More specifically, reciprocating internal combustion engines

- cannot supply any torque below a certain speed (*idling speed*);
- the maximum value of their torque (*wide open throttle torque*) is almost constant with speed, with the consequent impossibility to accelerate the vehicle at low speed with high power.

An ideal engine should deliver a torque even at zero speed, to start-up the vehicle and should be able to accelerate the vehicle at its rated power at any value of speed. These deficiencies compelled use of a suitable gearbox and a clutch. For this reason a section is dedicated to the evolution of the gearbox and its start-up device, in its two main variants of manual gearbox with friction clutch and automatic gearbox with torque converter.

In consideration of the complex nature of the transmission of the early cars, it is possible to argue that the weight advantage of the spark-ignition engine (including its tank) was partially jeopardized by those heavy gearboxes. In addition, the combined

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operation of the clutch, accelerator and brake by the driver, and the starting of the engine by means of a crank were perceived as discouraging by many customers of the first automobiles, who felt they needed the assistance of a professional driver or, at least, mechanician.

The above problems stimulated many manufacturers to apply to their car either electric motors or steam engines that could be governed by a single and simple control. For this reason, an additional section will be dedicated to these two kinds of prime movers.

4.1 Combustion Engines Before the Automobile

The first thermal engine is ascribed to Heron who developed it about 130 B.C.; it was operated by the reaction torque due to two steam jets mounted on a rotating pivot.

Reciprocating steam engines, that later inspired internal combustion engines, were developed between the second half of the 18th and the beginning of the nineteenth century. One of these early steam engines, powering the first self-propelled vehicle developed by Nicholas Cugnot and tested in 1769, is shown in Fig. 2.22.

It is impossible to identify a single person as the inventor of the internal combustion engine; many different attempts were made and many different solutions were tried. One of the first ideas for such an engine can be attributed to the famous astronomer and mathematician Christiaan Huygens who designed a machine at the end of the seventeenth century to raise the water for the gardens of the castle of Versailles. His engine was inspired by a piece of artillery and, thus, its fuel was gun powder.

On the contrary, the priority for the first vehicle operated by an internal combustion engine is certain; this vehicle was invented, designed and tested in 1807 by Issac De Rivaz, after many fruitless attempts performed since 1780 to build a steam vehicle. A scaled down model of this vehicle is shown in Fig. 4.1. Its engine, forerunner of a generation of similar machines, is based on a piston, free to move in a vertical cylinder, together with a rod connected to a chain. The chain was wound on a pulley with horizontal axis: This chain-pulley device is equivalent to a rack-pinion mechanism.

The fuel for this engine was gas contained in a balloon; it could be lighting gas, obtained from the combustion of coal, or pure hydrogen, obtained in a laboratory by the reaction of sulfuric acid with metallic zinc. A certain quantity of gas was introduced into the combustion chamber at atmospheric pressure and ignited by an electric spark. The energy of combustion launched the piston upward; at the end of the piston stroke the combustion gases were exhausted through a valve, leaving the combustion products in the cylinder at atmospheric pressure; at this time the exhaust valve was closed.

The cooling down of the gas caused the cylinder pressure to decrease below its atmospheric value. The piston weight and the ambient pressure forced the piston to return to its initial bottom position slowly; the energy coming from the combustion was partly changed into useful work by the piston descent. A ratchet mechanism

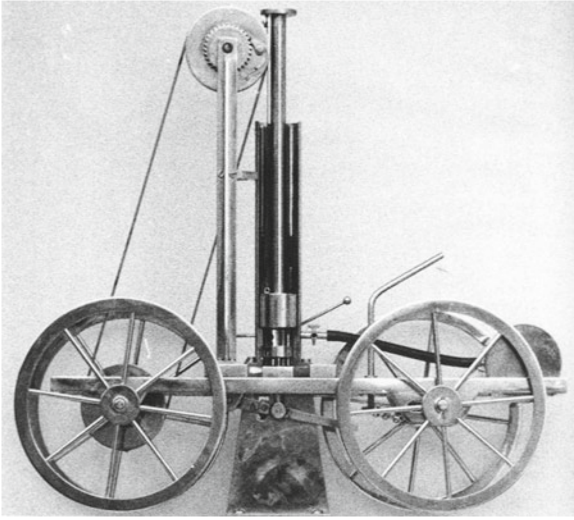

Fig. 4.1 Scaled down model of the vehicle of Issac De Rivaz, tested in 1807 (from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

connected the wheel with the chain moved by the piston; this mechanism moved the driving axle through a rope transmission.

This family of internal combustion engines, where the internal pressure becomes lower than the ambient pressure during the work phase, were called *atmospheric engines*. The useful work was produced by the atmospheric pressure working against the partial vacuum in the cylinder.

Timing the engine, such as opening or closing intake and exhaust valves or igniting, was accomplished manually, by the driver. De Rivaz described in his reports a vehicle of 900 kg of mass; the engine piston had a bore of 365 mm and a stroke of 1.5 m; the vehicle speed depended on the ability of the driver to operate engine controls quickly. During the official test, the vehicle drove for 9 m, at each engine stroke, accomplished in 5 s, corresponding to a speed of about 7 km/h.

A similar mechanical architecture is shown by the engine of Barsanti and Matteucci; however an important improvement was achieved by timing the engine automatically, as in modern engines. The fuel was still gas, therefore not very suitable to be carried on board a vehicle. A scale model of this engine is shown in Fig. 4.2.

Niccolò Barsanti (1808–1864) was a professor of Mechanics and Hydraulics at the Ximenian Institution in Florence; Felice Matteucci (1821–1887) was a brilliant mechanical engineer specialized in the design of canals and dams, to reclaim the marches in Tuscany. They started studying gas combustion in 1851 and in 1853 they filed officially a sealed document at the Academy of Georgofili. This document described in details the results that could be obtained with a gas combustion engine

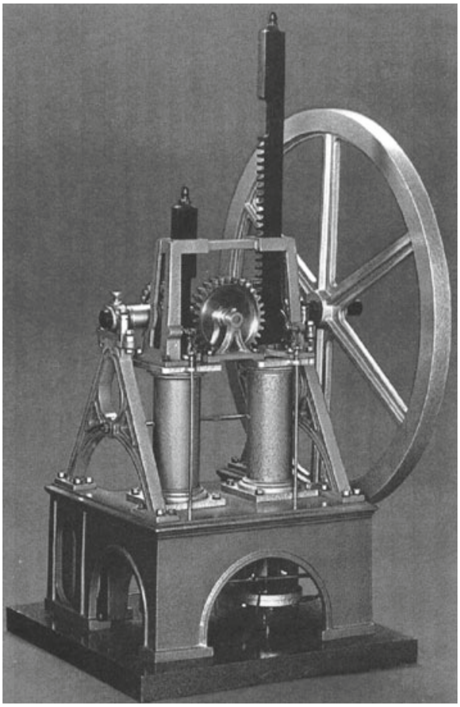

Fig. 4.2 Scale model of the first atmospheric engine of Barsanti and Matteucci tested in 1854 (from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

they invented; the contents of these documents were disclosed only in 1863, when they had demonstrated the performance of their engine with working prototypes.

The first prototype was working in 1854 and in the same year they obtained a patent in England. Later they patented the engine in different Countries. These patents did not regard the engine thermodynamics, already known from the papers of Carnot, but the mechanisms that enabled the engine to work automatically. The first engine delivered to a customer was built by Benini Works in Florence and installed to operate the railway machining shop in the same town.

This engine features two pistons; one of them is shown as detail *a* in Fig. 4.2 (the figure numbers refer here to the drawing, taken from the original patent, reported in Fig. 4.3). The piston rod is connected through a ratchet to a gear wheel *b,* operating the shaft *c,* that can be seen in Figs. 4.1 and 4.4. The piston is launched upwards by the combustion energy and stops as the combustion products are exhausted by the sleeve valve *f* in Fig. 4.3. From this time on, the return phase begins under the action of atmospheric pressure that is higher than the internal pressure. The descent motion causes shaft *c* to rotate*;* the speed of this shaft is made regular by a flywheel (see Fig. 4.2) and by a second piston with opposed phasing.

The same shaft moves, with a crank and a connecting rod, the yoke *d* in Fig. 4.3; its motion is phased with that of the piston and opens and closes the sleeve valve *f*; the function of the piston *e* is to improve the scavenging of the combustion chamber

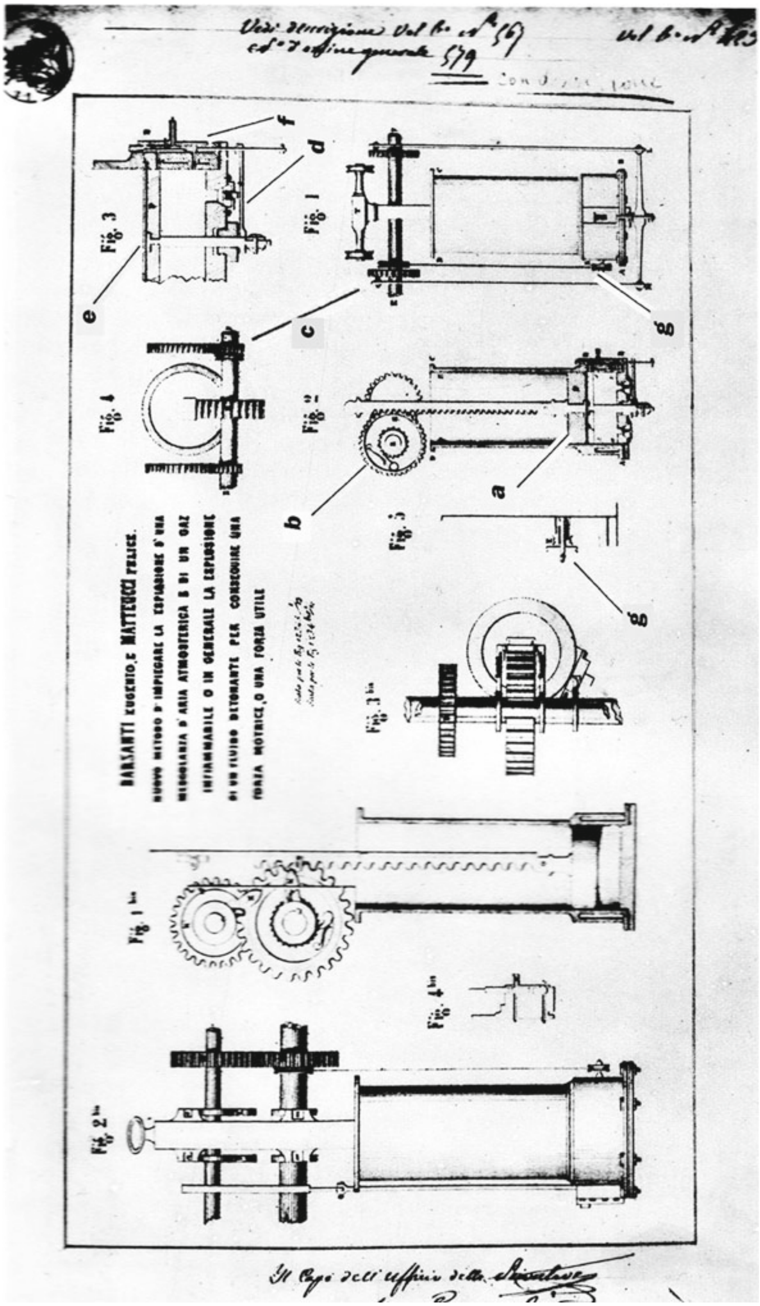

Fig. 4.3 The Barsanti and Matteucci engine features two pistons; one of them is shown as detail *a*. The piston rod is connected with a ratchet to a gear wheel *b* rotating together with shaft *c* (from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

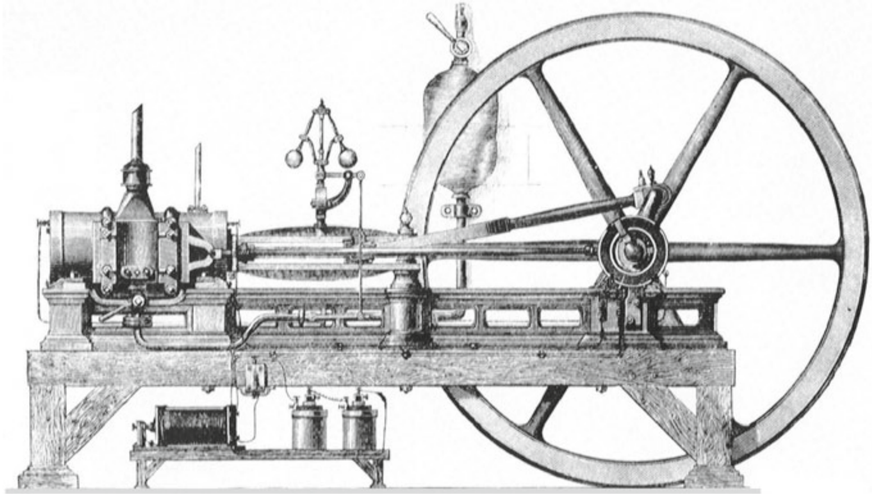

Fig. 4.4 The Lenoir's combustion engine is similar to a reciprocating steam engine (from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

at the end of the descent stroke. An electric ignition is given by an electrode *g* in Fig. 4.5; this electrode is connected to a battery, that has a voltage multiplier with a contact operated by the motion of yoke *d*. The drawings, labelled as '*bis*' refer to a second simpler version of this engine, without the counterpiston *e*.

The two partners founded a Company for the production of these engines in 1860, but the untimely death of Barsanti in Lieges interrupted the operation of the company before reaching any commercial success.

The first successful company producing internal combustion engines was founded by Jean Joseph Lenoir (1822–1900), the first to produce and sell in different Countries a significant quantity of engines (about 600)backward, if compared with atmospheric engines from the standpoint of thermodynamics, because it works without a compression phase. The aim of Lenoir was, however, to develop an engine with a continuous and controllable combustion process, suitable to work as easily as a steam engine.

As a matter of fact, the Lenoir's engine is a reciprocating steam engine converted to internal combustion, capable of operating without the penalty of an external boiler. Figure 4.4 shows the engine in a drawing of that time.

There is a double effect piston working through a crank mechanism with cross-head; the crank operates also two sliding valves as in steam reciprocating engines, for mixture intake and exhaust. The cylinder has a water cooled jacket; two spark plugs are ignited by a battery with Rühmkorff voltage amplifier, located under the cylinder.

In actual operation, spark plugs controlled combustion at partial loads only, while at wide open throttle self-ignition prevailed, making the engine very noisy and rough, as customers claimed. Also the high gas consumption was considered as a weak point.

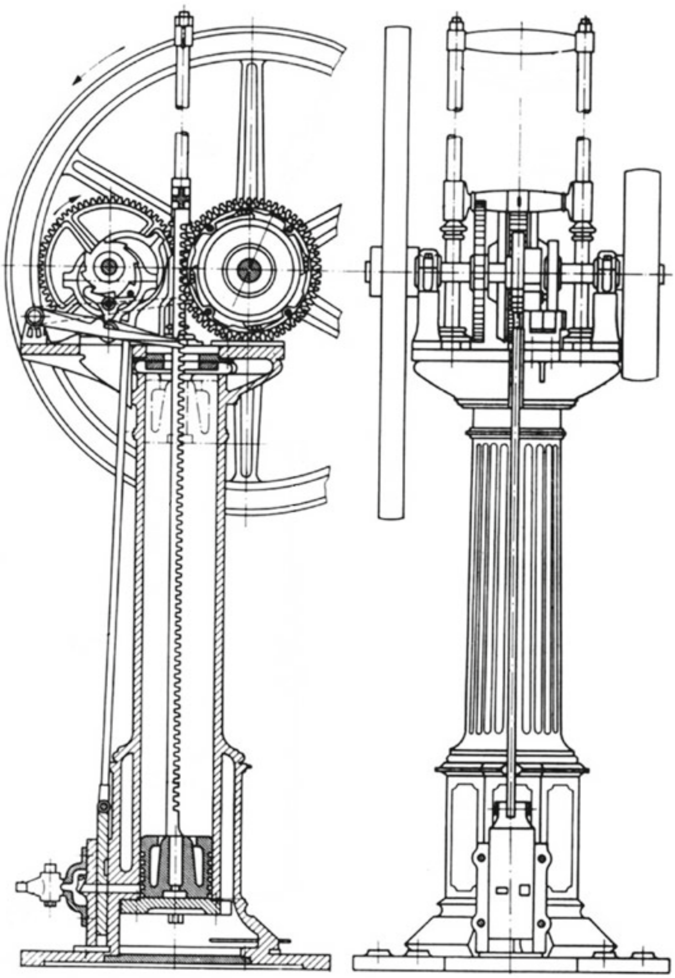

Fig. 4.5 An atmospheric engine by the Otto Co.; its strong point was the free wheel developed by Langen (from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

There is no mention of any vehicle working with his engine, even if there is a sketch from Lenoir on this subject.

Nicolaus August Otto (1832–1891) did not have the chance to receive a technical education suited to his ambitions, but his job as a travelling salesman allowed him to study Lenoir engines and to develop an interest in the subject. He spent all savings he could make from his revenue to experiment with and improve Lenoir engines and to make their combustion more gradual and controlled. He tried to introduce a compression phase in their working cycle, but without success. As a consequence, he started to build atmospheric engines.

When he had his first prototype under test, he had the chance to meet Eugen Langen (1833–1895), a dynamic technician who had already reached success in the introduction of new inventions. In 1864 they established together the Otto Co., with the aim of producing and selling compression engines.

Commercial success came after the 1867 International Exhibition in Paris where the Otto engine was granted a golden medal, as prize for the internal combustion engine with the lowest fuel consumption. About 3,000 engines similar to that in Fig. 4.5 were produced till 1882.

This engine was quite similar to that of Barsanti and Matteucci but the patents of the two Italian inventors concerned the automatic timing of the engine only; the free wheel connection of the Otto engine, developed by Langen, was different and better if compared with the ratchet wheel of Barsanti and Matteucci. A law suit for infringement started by Matteucci against Otto was lost by the former.

Encouraged by the success of the atmospheric engines, Otto devoted himself to accomplish his former idea of introducing the compression phase into an engine similar to that of Lenoir; Carnot's theory suggested this solution to be the best, but in practice was not achieving good results yet, because of preignition and self-combustion, problems caused by hot spots in the combustion chamber that were difficult to eliminate with the available technologies.

After many tests Otto developed a four strokes engine, in which one stroke was dedicated to mixture compression; in addition, the mixture inside of the combustion chamber was stratified, being richer in the region around the plug and leaner at the combustion chamber walls and piston top. With this idea, hot spots were virtually no longer dangerous. In his patent for a four stroke engine, filed in 1876, three claims regarded mixture stratification, only one four strokes operation.

This new engine, shown in Fig. 4.6, was provided with a shaft parallel to the cylinder axis, operating a sleeve valve 1 and a poppet valve 2, the first for intake and ignition, the second for exhausting combustion gases. Three ducts were machined in the head: one for combustion gas, one for air, the last for ignition. A flame of an external burner was brought to the combustion chamber at the time of ignition.

During the intake stroke, air was introduced at first and reached the combustion chamber 3, followed by a rich mixture of air with gaseous fuel, which remained in the recessed portion 4; and then the ignition flame was transferred into the recess, to start combustion. In consideration of the low speed of the engine, there was practically no mixing of the rich mixture with the dilution air, before ignition, obtaining the desired stratification.

Otto Co. and its licensees built about 40,000 engines of this kind, from 1876 to 1889. The patent made the concept of four strokes operation an exclusive asset of Otto Co.; it was protected very carefully by stopping similar projects developing in Germany and other European countries; however, a paper was discovered in 1884, describing in details the advantages of an engine based upon a four strokes operation. The content of this chapter, published by Alphonse Beau De Rochas in 1862, remained almost unknown for years and was not protected by any patent. A competitor brought this chapter to court and obtained a ruling invalidating Otto's patents, whose contents became available to everybody.

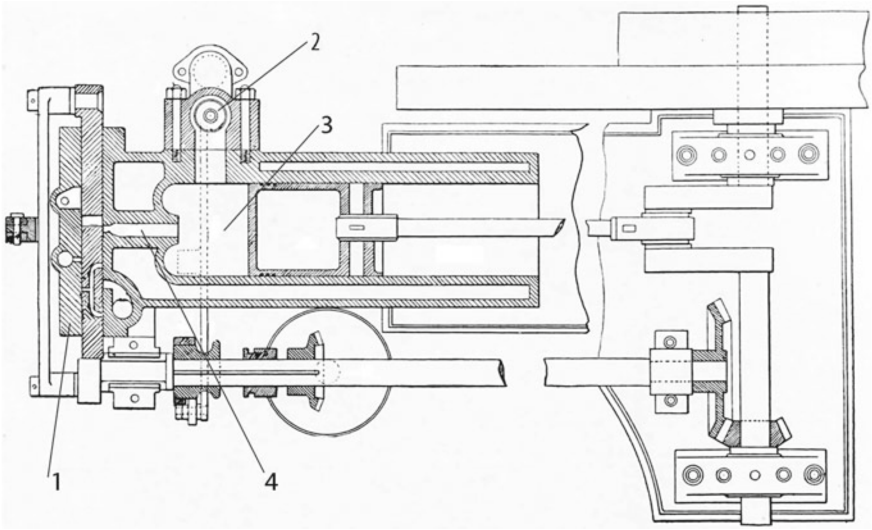

Fig. 4.6 The new Otto four strokes engine has a shaft parallel to the cylinder axis operating a sleeve valve *1* and a poppet valve *2*, the first for intake and ignition, the second for exhausting combustion gases (from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

Neither Otto's reputation nor his business were affected, but this sentence should be considered as a major event in history of technology, because it opened the market to many new engines and prepared the birth of the automotive engine.

4.2 Automotive Internal Combustion Engines

4.2.1 Mechanical Architecture

The first engine specifically developed for vehicular applications was designed by Gottlieb Daimler (1834–1900) and Wilhelm Maybach (1846–1929), both former employees of Deutz Co., the new name of the Otto Co., we mentioned in the previous section.

The main objective of their studies for a self-propelled vehicle—cars, bicycles, boats and railcars were considered by these inventors—was weight reduction and power increase. This target implied a different mechanical design, allowing a higher rotation speed and the application of a new fuel, easier to be carried on board the vehicle, with a higher energy density than coal gas.

Their choice fell on *ligroin*, a very light liquid oil distillate, with a vapor pressure slightly higher than current gasoline. The ease of evaporation made *carburetion*, the

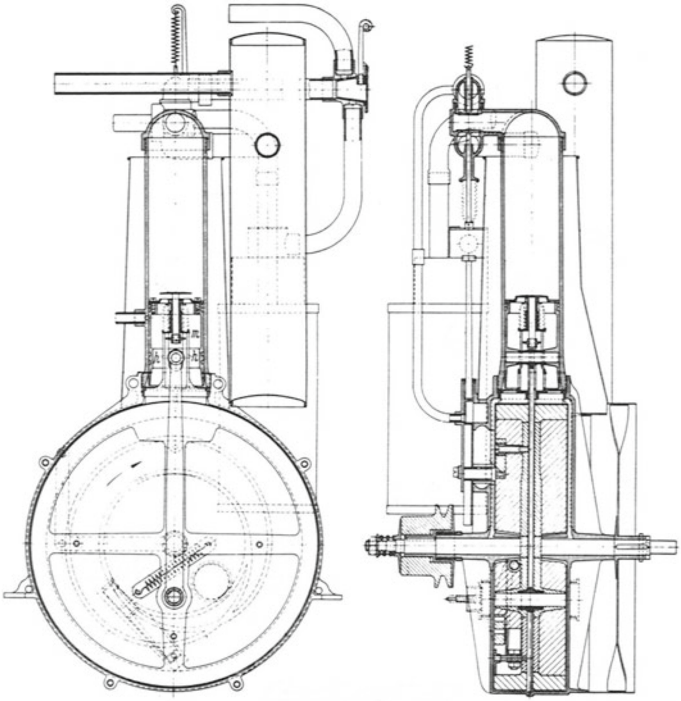

Fig. 4.7 In the first Daimler's engine the charge stratification is favoured by the long stroke and is obtained by a second intake valve on the top of the piston, opening at bottom dead center (from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

process of mixing air with a liquid fuel, simpler, but posed major safety problems. The carburetor was invented and designed by Maybach, after studies performed at Deutz; this Company, however, was not interested in this invention, addressed to fuels that were more expensive and unnecessary for stationary engines, the main product of Deutz.

The first Daimler's engine started operating in 1883; its displacement was 212 cm^3, with a maximum power of 0.5 HP at 600 rpm. Its specific power of 2.35 HP/l was much higher than the value of 0.5 HP/l, reached by stationary Otto engines. These engines received from their particular shape the nickname *Standuhr*, grandfather's clocks in German. The cross section of this engine reported in Fig. 4.7 shows some unusual detail.

The cylinder was made with a thin steel tube, cooled by an air stream, moved by a fan rotating with the flywheel. The charge stratification was favoured by the long stroke (about 1.7 times the bore) and obtained by a second intake valve on the top of the piston, opening at bottom dead center, through which a quantity of dilution air was blown into the combustion chamber by the pressure built up in the crankcase.

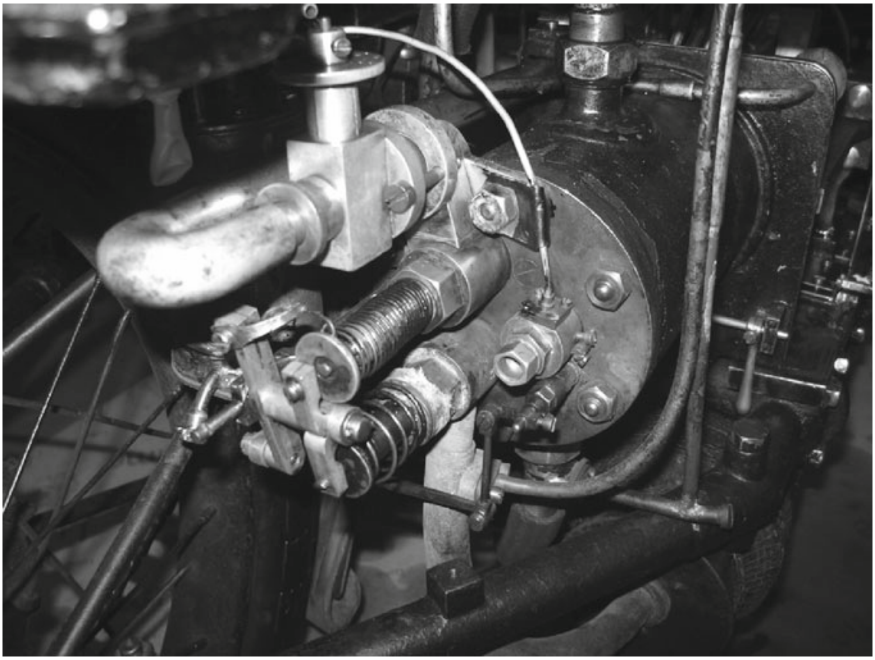

Fig. 4.8 The head of the Bernardi engine, with one of the first jet carburetors and, beside the valves, the ignitor (Museum of the University of Padova)

The main intake valve was automatic. The exhaust valve was operated by a double action cam, made by a spiral groove cut in one of the very heavy cranks. The cranks work also as flywheels and contribute to reduce the dead space in the crankcase, to increase its compression ratio.

The ignition was obtained by a glow plug, without possibility of adjusting the spark advance. The plug was made by a tube crossing the cylinder, with one end in the combustion chamber and the other end facing the flame of a lamp.

This engine was demonstrated, as a vehicle propulsion system, for the first time in 1886 on a motorcycle; the first car, presented in 1889, had a two cylinder V engine, derived from the first, with a displacement of 565 cm^3. This kind of engine had a wide diffusion in cars by many licensees all around the world. In particular, it powered the cars built by Panhard and Levassor and Peugeot in France, who were, at the beginning of the twentieth century, the most important car manufacturers in the world.

About ten years later engines were developed with both intake and exhaust valves opened by cams, as we can see on the tricycle built in 1894 by Enrico Bernardi (1841–1919) in Italy. The engine head with one of the first jet carburetors and the ignitor, is shown in Fig. 4.8. This single cylinder engine, with a displacement of 624 cm^3 delivered 2.5 HP at 785 rpm (about 4 HP/l).

No regulation valve was applied to the carburetor except for air to fuel ratio adjustment in cold operating conditions. Therefore the engine worked at wide open throttle always; its speed was controlled by a Watt regulator, like in steam engines, closing the intake valve to regulate the speed. The engine was therefore regulated with an on-off operation around the desired value of speed.

A similar regulation system is shown by the Daimler Phoenix engine in Fig. 4.9, built under licence by Panhard & Levassor. The Watt regulator, with centrifugal masses *e*, acts in this case on the exhaust valves; they will not be opened beyond a regulated speed limit, stopping combustion.

The combustion chamber featured two lateral appendages where the valves were installed with their stem parallel to the cylinder axis: the automatic intake valve *a* is at right and the exhaust valve *b* at left; close to the intake valve, the glow plug *c* and its heating lamp *d* can be seen.

This third generation engine of Daimler, still inspired by the first, shows a water cooling system and a more conventional cam shaft; the specific performance was doubled as compared with the first.

The devices addressed to obtaining a stratified charge were abandoned by Daimler at this time, because of an improved control of the mixture ratio, obtained with a jet carburetor, and the elimination of hot spots with water cooling.

In the following years, at the beginning of the twentieth century, no significant improvement in specific performance was made; to increase the performance of luxury and sports cars almost all manufacturers introduced engines with larger cylinder displacement and a higher number of cylinders.

This approach to increased performance can be justified by noting that the cars of that time were an exclusive product for wealthy customers: For them the high performance reputation of a car was important in making the purchasing decision. A high power (the most powerful commercial cars of that time featured about 60 HP at 4 HP/l) could only be obtained with a large displacement, it being still impossible to increase engine speed and compression ratio.

An example of this trend is shown in Fig. 4.10. The structure of these engines, mainly with four cylinders, was very bulky, made of two blocks (three blocks for six cylinders) including cylinders and heads in a single cast piece; a four or six cylinders engine was composed by installing two or three blocks on a single crankcase.

The combustion chamber of these engines was wider than the cylinder cross section, containing valves on a lateral appendage (lateral or bilateral valves, when intake and exhaust valve are at opposite sides); both valves were operated by camshafts that, despite their higher complexity, allowed pumping losses reduction as compared with automatic valves.

Most of these engines featured automatic carburetors, where air to fuel ratio was almost constant with engine speed and load and where load regulation was obtained by a throttle valve; speed regulators were therefore gradually abandoned.

On top of each cylinder head a tap (*decompression tap*) made hand cranking of the engine easier. It allowed introduction of an additional quantity of gasoline in the cylinder closer to compression, to compensate for the condensation of fuel on

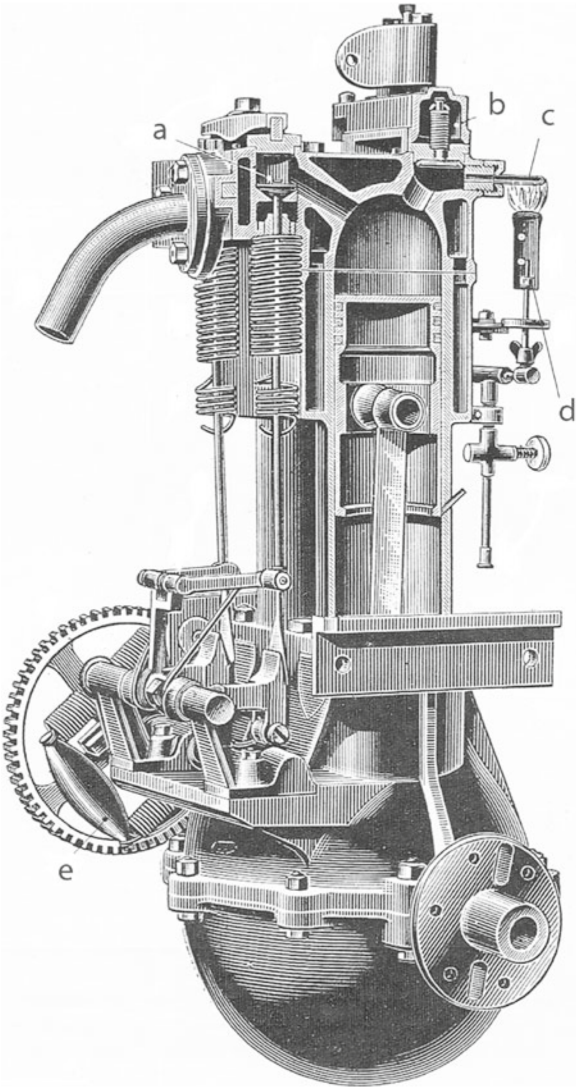

Fig. 4.9 Third generation engine by Daimler: the Phoenix. It was still inspired by the first, but features a water cooling system and a more conventional cam shaft (redrawn from Baudry de Saunier 1905)

cold manifolds and to reduce compression pressure in non-firing cylinders. The cross section of a two blocks engine with this architecture is shown in Fig. 4.11.

The layout with lateral valves on one side of the block became widely common and was applied for its simplicity till the 1940s. The long connecting road, used to reduce the lateral loads on the cylinder wall, was typical of the engines of this generation.

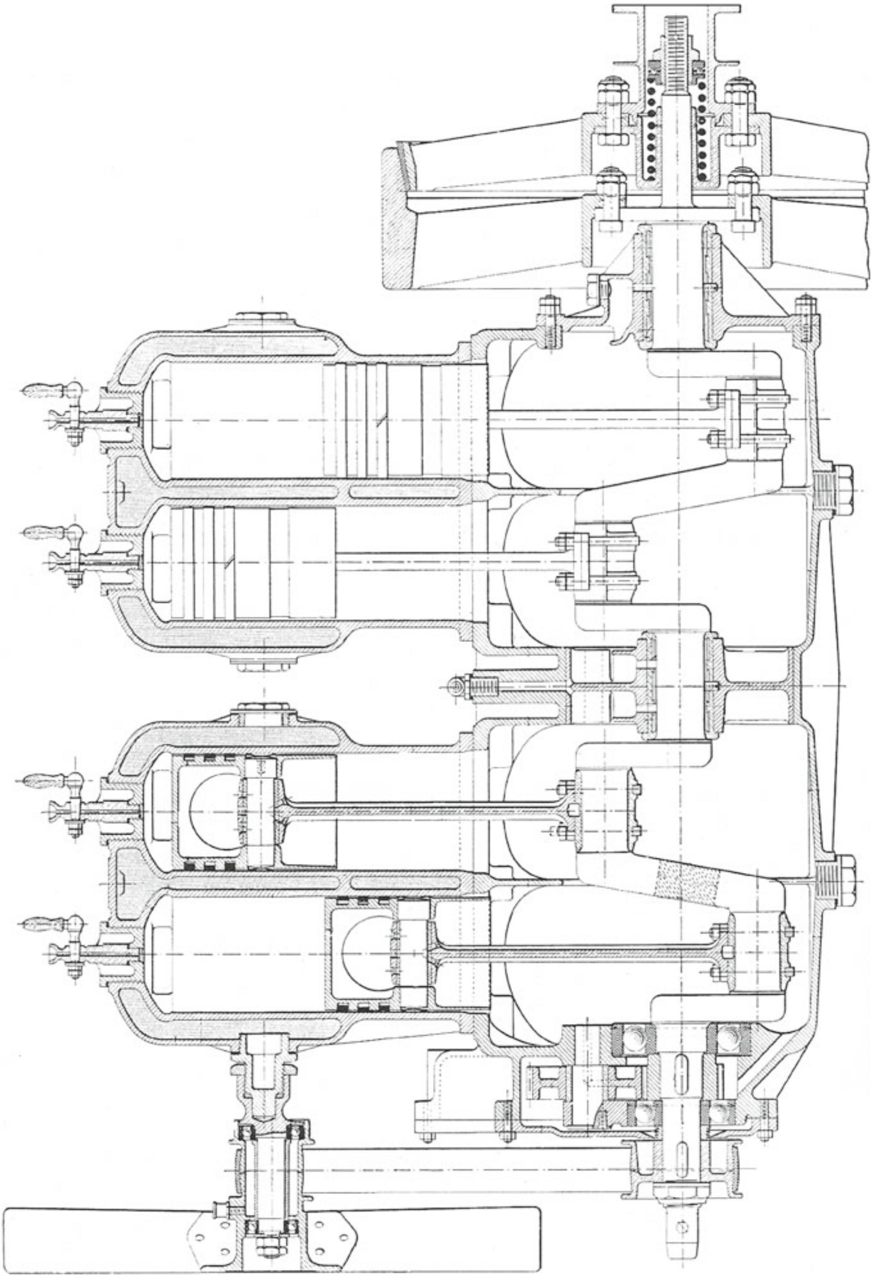

Fig. 4.10 The structure of four cylinders engines of the 1910s featured two blocks, including cylinders and head in a single cast piece (redrawn from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

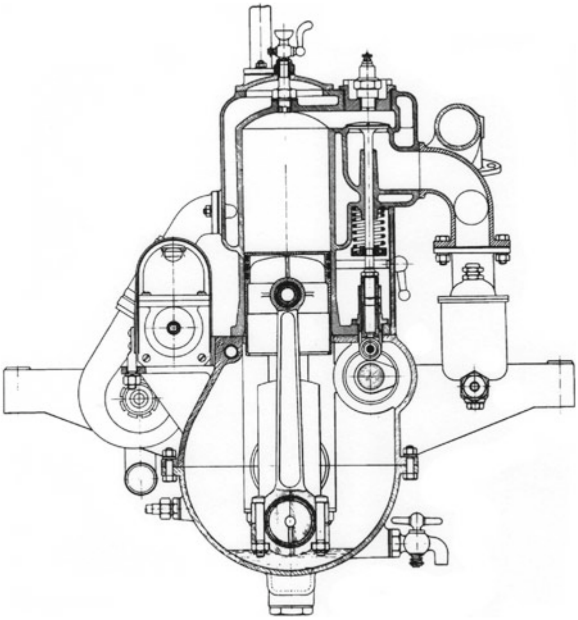

Fig. 4.11 Cross section of a two blocks four cylinder engine, the first produced by Alfa Romeo starting from 1910 (from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

The valve seats were reached from the top for machining, because it was impossible to disassemble the head from cylinders, each valve chamber was closed by a removable bronze plug: One of these plugs could be drilled to obtain the spark plug hole. Glow plug ignition was abandoned in favour of magneto ignition.

The 1922 Lancia engine, shown in Fig. 4.12, is one of the first where performance was improved by increasing the engine speed. In these years, particularly in Europe, a trend toward decreasing displacements was encouraged by the high price of gasoline and to the taxes that almost every country applied on the basis of the engine displacement.

In this and other engines two typical features of modern engines appear: a structure including a detachable cylinder head and a cylinder block that includes the crankcase and the oil sump (*monoblock*) and overhead valves. The Lancia engine had other technical features that made it unique among competitors, such as cylinders in a narrow V arrangement and an overhead camshaft. The 1934 Bianchi engine, shown in Fig. 4.13, featuring a cam shaft in the block with push rods is probably a more appropriate example of the state of the art of these years.

Nevertheless, many engines of this time still had lateral valves, particularly in cheap high volume cars; the ratio between the length of the piston and connecting rod and the bore are closer to the current state of the art, because of improvements in bearing materials. Molded parts had also a reduced thickness.

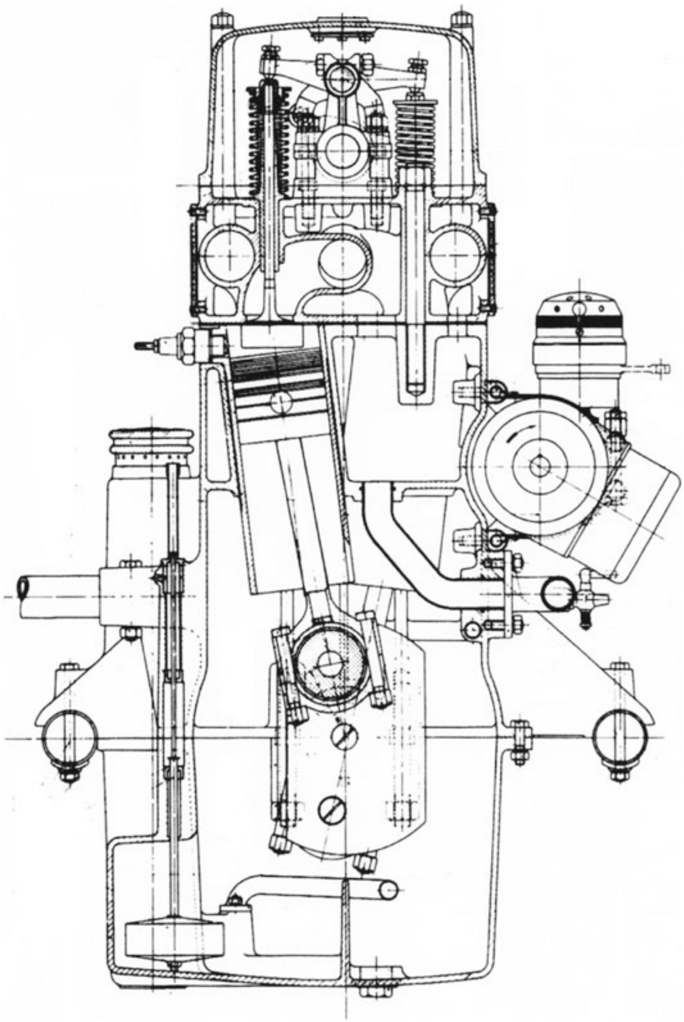

Fig. 4.12 A 1922 Lancia engine in which two modern features appear: detachable cylinder head and overhead valves (courtesy of FIAT Historical Archives)

Some engines built between 1910 and 1930 were very different from the dominant rules. Poppet valves, that had been widely applied since the beginning of the automotive industry, were a source of many problems. They implied fabrication problems, particularly in non-separable heads, and operation problems because of wear and dirtiness of their seats. This last issue caused the need for periodic cleaning and re-machining of the seat. A last reason for complaints by customers was their noisy clicking, so that some manufacturers tried to avoid all these negative points, at least for luxury cars.

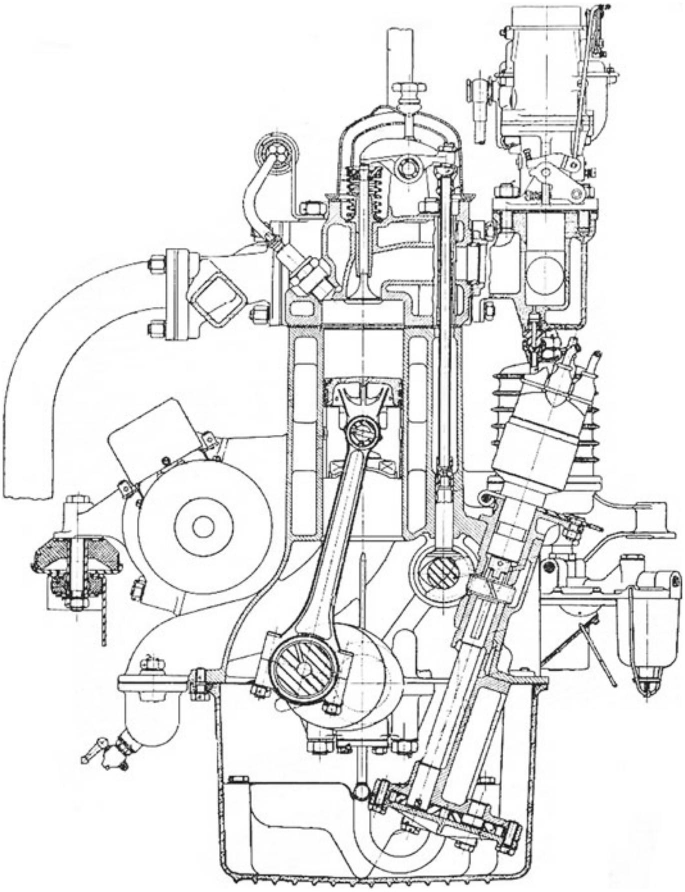

Fig. 4.13 1934 Bianchi engine, featuring a cam shaft in the block, with push rods (redrawn from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

Many proposals of different valve systems were made; the Knight's patents, developed in the United States in the first years of the twentieth century, were bought and applied by some European car manufacturers, as Panhard and Levassor in France, Daimler in Germany, while Itala, in Italy, developed its own patent.

Figure 4.14 shows a cross section of the 1912 Panhard and Levassor '*Avalve*' engine, probably the first application of this kind of engine that remained in production till the 1930s. The meaning of *avalve* was *without valves*, but valves still existed in a different arrangement, made with sliding sleeves (*a* and *b* in the figure) around the piston. On these sleeves suitable openings were cut that constituted the intake and exhaust ports: the internal sleeve was also used as piston liner. Both sleeves were moved by a crank and rod mechanism *c*, turning at half of the speed of the engine.

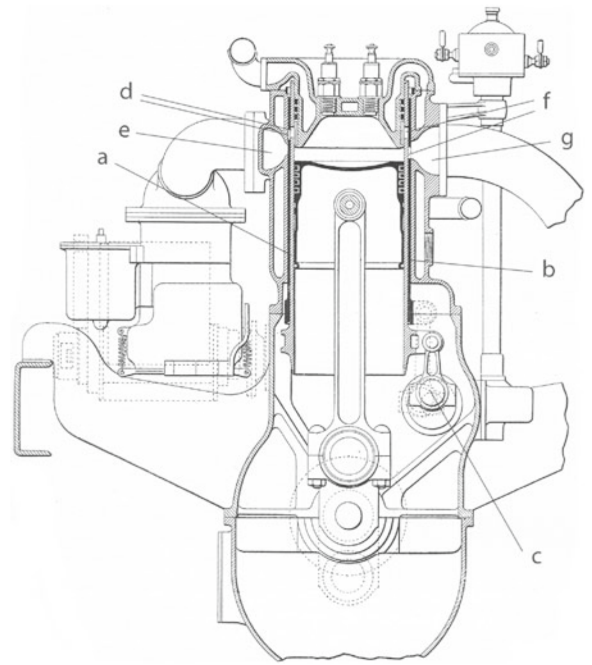

Fig. 4.14 Avalve engines had valves made with sliding sleeves, fit around the piston. Both sleeves *a* and *b* were moved by a crank and rod mechanism *c* turning at half of the speed of the engine (redrawn from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

Sleeve cuts *d* opened the intake ports *e*, while sleeve cuts *f* opened the exhaust port *g*; segments were necessary also on the cylinder head to have appropriate tightness.

These engines were claimed to be so quiet as it was impossible to hear the engine idling; as a major drawback, a significant friction between sleeves and cylinder liner increased consumption and affected performance negatively.

The improvements in poppet valves materials, in machining tolerance and particularly in gasoline, that reduced tar deposits on seats, made the advantages of sleeve valves to disappear.

A new valve design was introduced in aircraft engines and transferred to race car engines and later to high performance commercial engines; these engines were provided with semi-spherical combustion chambers with inclined poppet valves. The shape of the combustion chamber, with its walls closer to the spark plug, reduced engine octane requirement and made larger poppet valves applicable with advantages in performance.

Examples of this new technology, widely used in present engines, were the Alfa Romeo engines after 1928; overhead valves were operated by a twin overhead camshaft making top speeds of 4,500 rpm, very high for that time, possible.

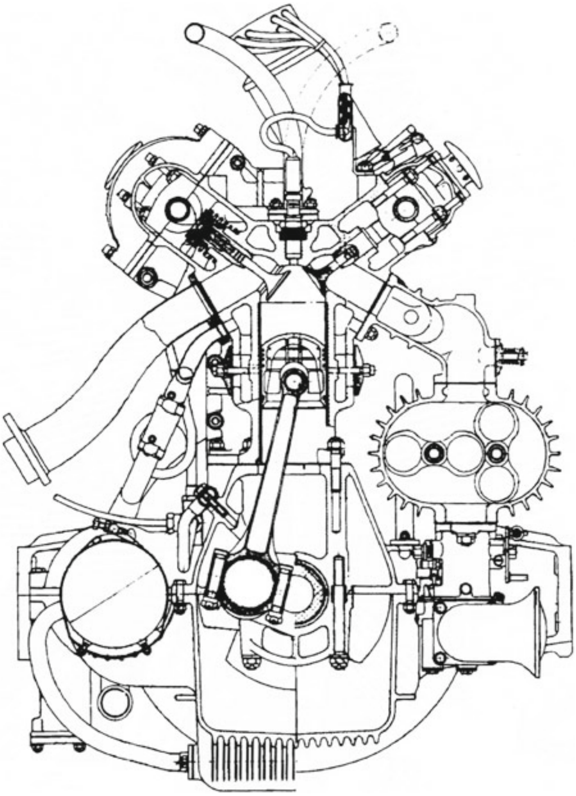

Fig. 4.15 A new design of 1937 with inclined overhead poppet valves was based on a semi-spherical combustion chamber (redrawn from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

One of these engines is shown in Fig. 4.15; It is the 1937 8C 2900 B, an in-line eight-cylinder supercharged engine that reached about 62 HP/l, an impressive figure for that time. Most engines, however, featured parallel valves till the 1950s when many examples of semi-spherical combustion chambers were in production, both with overhead or push-rod cam shafts.

This short report on architectural evolution is concluded by the 1974 Volkswagen engine, shown in Fig. 4.16. It is an example of a new breed of cheap and rational engines, with parallel valves and overhead camshaft, operated by an elastomeric timing belt. Valves are aligned to simplify the head design, and a suitable shape of the combustion chamber is obtained by designing a cavity in the piston top (cup chamber) or around the valves (pent-roof chamber).

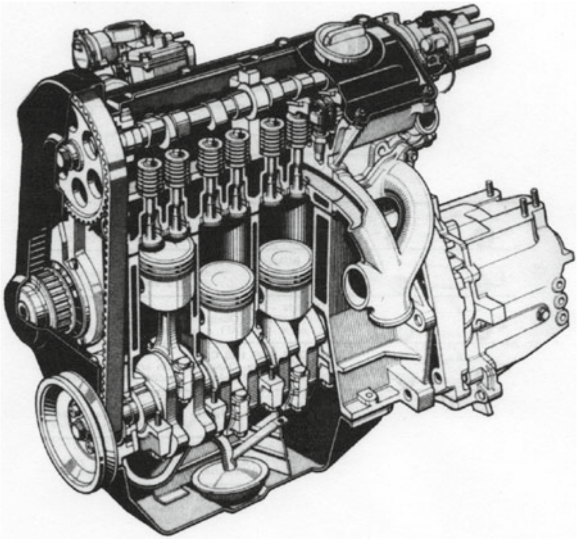

Fig. 4.16 The 1972 Volkswagen engine is an example of a new breed of rational engines with parallel valves and overhead camshaft, operated by an elastomeric belt (from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

4.2.2 Structural Components Technology

A picture of the results obtained in about 100 years of engine evolution can be obtained by comparing the performance of the last engine described with that of the first Daimler engine:

- Specific power: from 2.3 to 60 HP/l (from 1.7 to 45 kW/l).
- Rotation speed: from 600 to 6,000 rpm.
- Compression ratio: from 2.5 to 9.
- Specific mass: from 180 to 1.35 kg/HP (240 to 1.8 kg/kW).

If the most important commercial car engines produced in Europe from the beginning to the 1980s are taken into account, the plot of the engine specific power versus the year of commercial launch shown in Fig. 4.17a can be obtained. This progress was allowed by the evolution of materials and production technologies and by new inventions.

An important issue in engine performance was the tightness of exhaust valves and their life since leaking valves caused loss of performance and started a process of quick deterioration of their seat. After sleeve valves, traditional in steam engines, were abandoned, poppet valves became a standard solution but they required a perfect match between the bevel surfaces of the valve and its seat. This result was initially obtained by adjusting each valve on its seat, because machining tolerances were too wide to provide tightness after assembly.

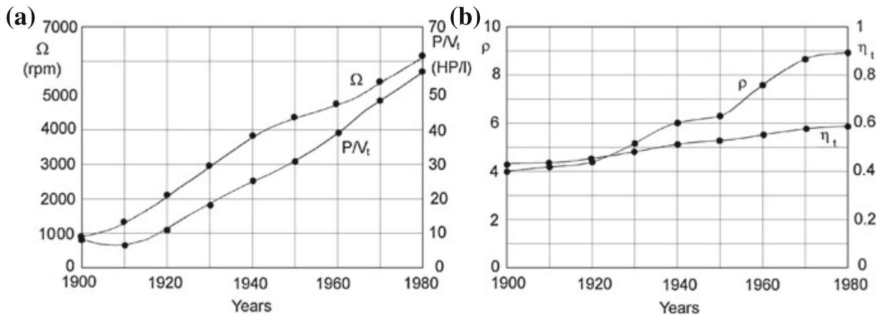

Fig. 4.17 Evolution of reciprocating spark ignition engines in the years 1900–1980. **a** Specific power P/V_t (in HP/l) and rotational speed Ω (in rpm); **b** Compression ratio ρ and thermodynamic efficiency η_t (from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

The valve was temporarily assembled on the engine head and then rotated by a screwdriver, after having sprinkled the matching surfaces with abrasive dust; an easy access to the valve was thus required for this operation that had to be repeated from time to time as a current maintenance operation.

The seat and the stem guide had also to be machined and therefore the engine head had to offer a suitable access to machining mandrels. When the early car engines were manufactured, no existing material could offer a suitable sealing to combustion pressure between engine head and cylinder block and therefore these two parts were made in a single piece, where access holes were provided for drilling and machining valve seats. These holes were closed by plugs.

This feature is shown in Fig. 4.18a for an engine with bilateral valves and in Fig. 4.18b for an engine with one overhead and one lateral valve; in both cases, a hole in the centre of the head (decompression tap in a, intake valve in b) is provided, to allow access for the mandrel used to bore the cylinder surface. In both cases the valve size was reduced for machining, a thing that decreased the engine volumetric efficiency and the overall performance.

Another design detail, that was quite different from current practice, was the bearing length, that had to be as wide as the shaft diameter because of the low value of oil pressure, usually introduced in the bearing by dripping. The consequence of the long bearings can be seen also in the connecting rod head width and, more in general, in engine length and weight. Moreover, the low lubrication pressure caused also piston wear and, to provide a sufficient engine life, the connecting rod had to be long enough to reduce lateral thrust.

To better understand the difference between current and old engines, the connecting rods of two engines of about the same displacement but dating back to the 1920s and to the 1960s, are compared in Fig. 4.19. The bulk and weight of the blocks and the whole engines were obviously a consequence of these dimensions.

Moreover, casting technologies initially available affected the design practice. Casting processes were developed to give iron ingots a shape as close as possible to

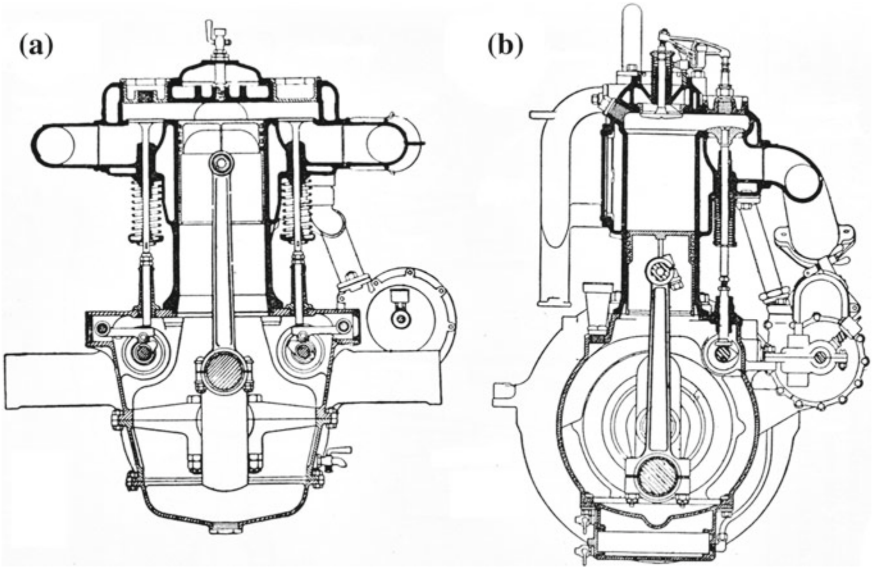

Fig. 4.18 Valve seat arrangement in an engine with bilateral valves (**a**) with one overhead and one lateral valve (**b**) (from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

the final shape of the part to be produced. Casting took benefit from the relatively low melting temperature ($<1{,}100\,^{\circ}$C) of this material and similar processes were applied to produce castings made of aluminum, brass or bronze. The traditional method, thousands of years old, for casting metals used sand moulds.

Simply stated, in sand casting a pattern is placed in sand, to make an imprint, and the resulting cavity is filled with molten metal. Then the metal is allowed to cool, until it solidifies to the desired shape, the sand mould is broken away, and the casting is removed. The outer shape of the pattern must reproduce the shape of the desired casting, taking into account the volume reduction (*shrinkage*) of the metal during cool-down and must incorporate a gating system.

Even if the origins of sand casting date back to ancient times, this process is still the most widespread. Typical parts made by sand casting were and are engine blocks, cylinder heads, gearbox and differential housings.

Silica sands (SiO_2) are mostly used. Sand is a product of the disintegration of rocks over extremely long periods of time. They are inexpensive and suitable as mould material because of their resistance to high temperatures. Several factors are important in the selection of sand for moulds: sand having fine, round grains can be closely packed and form a smooth mould surface. Good permeability of moulds and cores allow gases and steam produced during casting to escape easily.

The mould should have good collapsibility to avoid defects, since castings shrink while cooling. The selection of the sand involves certain trade-offs with respect to

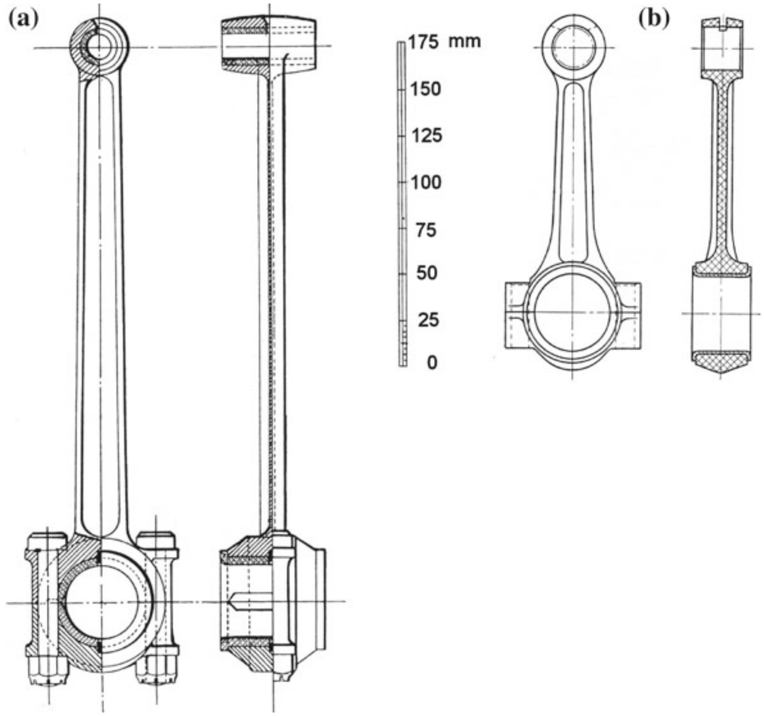

Fig. 4.19 Drawing of a connecting rod from the 1910s (**a**) and from the 1960s (**b**) for a cylinder with a displacement of about 500 cm^3 (from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

properties. Sand is now conditioned before use and mills are used to uniformly mix sand with additives. Clay is often used in moulds as a cohesive agent to bond sand particles, increasing sand strength.

There are three basic types of sand moulds available now: green-sand, skin-dried and dry-sand. The most common mould material is green moulding sand and was the only one available to produce the early engines. The term *green* refers to the fact that the sand in the mould is wet while the metal is being poured into it: Green moulding sand is actually a mixture of sand, clay, and water; it is the least expensive and most easily used material for moulds.

In the skin-dried method the mould surfaces are dried, either by storing the mould in air or drying it with torches. Skin-dried moulds are generally used for large castings because of their higher strength.

Sand moulds dried in ovens are stronger than green-sand moulds and allow one to obtain better dimensional accuracy and surface finish. In modern sand casting, various organic and inorganic binders are blended into the sand to chemically bond the grains for greater strength. These moulds are dimensionally more accurate than green-sand moulds but are more expensive; dimensional accuracy allows one to obtain sharper edges and thinner walls.

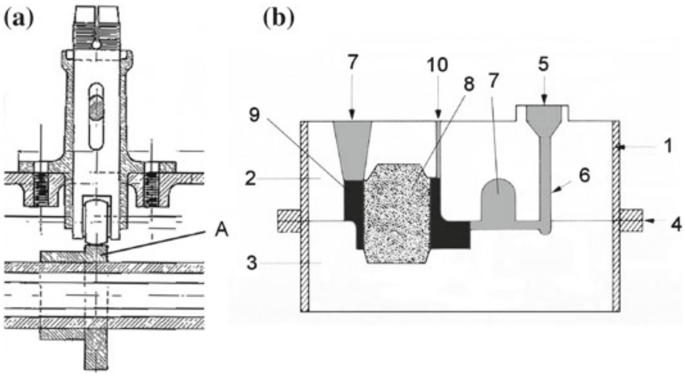

Fig. 4.20 The cam A in sketch **a** is taken as an example to describe a typical casting mould in **b**. The moulded piece *9*, i.e. the cam, needs a core *8*, to obtain the internal hollow. The mould is contained in a flask *1* and is divided in two parts, the cope *2* and the drag *3*, separated by a parting line *4*, positioned following the shape of the piece. The liquid metal is poured into the pouring cup *5*, through the sprue *6* and overflows through the risers *7*. The cooled metal contained in elements *5*, *6* and *7* must be removed from the casting

The most important parts of a mould are shown in Fig. 4.20, where the mould for one of the cams of the camshaft of an engine of the 1910s is sketched.

- The mould is supported by a flask 1. A two-pieces mould, like this, consists of a cope 2 on top and a drag 3 on the bottom. The seam between them is the parting line 4. The cope and the drag are filled with sand, represented in white in the sketch; the cam 9 to be cast is represented in black.
- The molten metal is poured into a pouring cup 5.
- The molten metal flows downward through a sprue 6.
- Risers 7 supply additional material to the casting as it shrinks during solidification. In the figure a blind riser and an open riser are represented.
- Cores 8 are inserts made from sand. They are placed in the mould to form hollow regions as the cam hub to be fit on the camshaft.
- Vents 10 are placed in moulds to carry off gases produced when the molten metal comes into contact with the sand.

After cooling, solid metal has filled also the areas 5, 6, 7 and 10, shown in grey. They must be cut away from the casting.

As a consequence of the brittleness of sand cores, the water jackets of the early engines had to be oversized; also fillet radii had to be conveniently wide to avoid cracks at the edges of the green sand contained in the top and in the drag.

A guideline drawing with suggestions for safe dimensions, from an engineering manual of the 1920s, is shown in Fig. 4.21 and gives an impression of that situation. As a result of these design rules, cylinders had to be grouped in blocks of two or three, so that four or six cylinder engines had an additional penalty in their length.

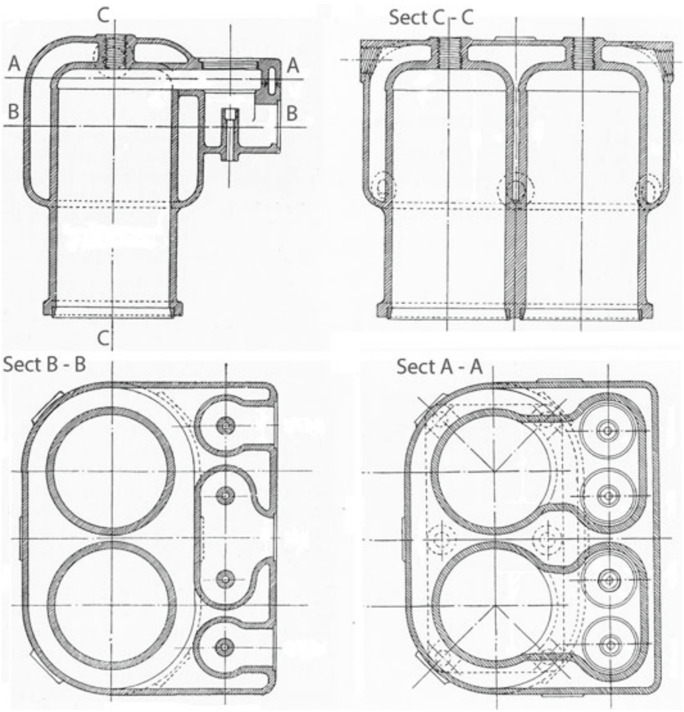

Fig. 4.21 Suggested proportions for an engine block with 1910s foundry technology (redrawn from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

Later, the use of cured sand allowed reduction of casting thickness and obtaining of sharper edges, with a consequent reduction in overall dimensions.

A few figures highlight the difference in size between two engines, one from the 1910s, the second from the 1970s:

- Ratio between connecting rod length and stroke: from 3.5 to 1.4 at present;
- Ratio between engine height and stroke: unchanged at 6;
- Ratio between the distance between the cylinder centres and the bore: from 1.3 to 1.1 at present;
- Block walls thickness: from 8 to 4 mm at present.

The unchanged value of the ratio between the engine height and stroke refers to different engine layouts, from a lateral valve engine with camshaft in the block, to an overhead valve and camshaft engine.

While the ratio between the weight and the displacement of engines didn't change much, the reduction of the ratio between weight and rated power is clear. The impressive increase of engine speed, shown in Fig. 4.17a, can be ascribed to the reduction in weight of the reciprocating parts and the improvements in lubrication and wear resistance.

If the curve is compared with that regarding the specific power, a significant part of the increase in performance can be ascribed to the improvement in rotational speed. Other reasons are improvement of the design of combustion chambers and of gasoline octane value.

The wide shape of old combustion chambers was due to the design limitations on valve layout that has been already described. As early as in 1919, combustion studies had shown the potential advantages of combustion chambers walls closer to the spark plug electrodes. As soon as technologies allowed overhead valves of larger size in comparison with bore to be applied, engine designers took advantage of this opportunity. An indirect demonstration of this trend can be offered by Fig. 4.17b where the compression ratio evolution is reported; on the same diagram the ensuing improvement of thermodynamic efficiency is also shown.

4.2.3 Carburetors

Early gasoline engines used surface carburetors to produce the air-fuel mixture. An example is the carburetor that was used on the engine of the Patent Motorwagen built by Benz, shown in Fig. 4.22a.

In carburetors of this type, an air stream entering the carburetor through the suction port A, was enriched by gasoline vapors simply by contact with the fuel F contained in the tank; the mixture left the carburetor through the outlet C, where some device, like the shield D, was provided to avoid fuel droplets being swept away by the air stream. The float B allows measurement of the gasoline volume.

This was the reason why a very volatile fuel was preferred in the first engines; this system featured heavy drawbacks in safety, because any backfire from the engine was likely to ignite the whole tank content.

Also Daimler's carburetor, designed by Maybach, was a kind of surface carburetor where some improvements had been introduced: Here the mixture formation was obtained by bubbling air through gasoline, as shown in Fig. 4.22b. The surface of the gasoline in the tank was completely covered by a float, to keep circulation of air in the fuel constant in spite of the changing fuel level. Again, separators were provided to avoid that fuel droplets could be swept away by air stream. Some wire mesh was also used to avoid backfire from the engine reaching the fuel.

The first jet carburetors appeared at the beginning of the twentieth century; in this kind of carburetor the air and fuel mixture was obtained by spraying gasoline in the air stream flowing in a tube, called *barrel*. Air was sucked through an intake *a* and a regulation valve *b* (in this case a rotary sleeve valve) was introduced in the intake manifold, as it is shown in Fig. 4.23. The gasoline was sprayed through a nozzle *c* by the pressure gradient between the manifold and the ambient.

Since the gasoline was sent to the carburetor by gravity or by other means, a float valve *d* in the carburetor avoided fuel spill; the float was designed to bring gasoline to the mouth of the nozzle when vacuum was not applied.

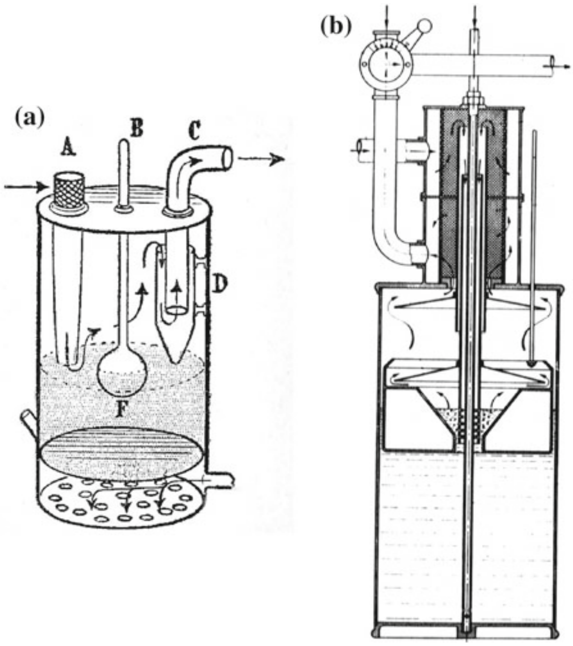

Fig. 4.22 Surface carburetors. **a** In Benz's surface carburetor a stream of air, entering through the suction port A, was enriched by gasoline vapors, simply by contact with the fuel F contained in the tank. **b** In Maybach's surface carburetor some improvement have been introduced; here mixture formation was obtained by bubbling air through gasoline (redrawn from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

When it was impossible to install the fuel tank higher than the carburetor, a manual pump was used to pressurize the tank; sometimes the exhaust gas pressure was used for this purpose.

Carburetors featured usually two barrels, as in the example in the figure; the larger barrel was used for normal operation, while the smaller was dedicated to idle operation.

Since fuel rate depended upon manifold vacuum, high at low torque, low at wide open throttle, the mixture tended to be leaner at high load and richer at low load; to avoid this natural tendency it was necessary to adjust manually the fuel orifice within an acceptable range. This adjustment was avoided by modifying the larger carburetor barrel with the application of a convergent/divergent restrictor a, as shown in Fig. 4.24. This was introduced in the 1910s.

The restrictor, shaped using the geometry defined by Venturi in 1780, caused a local pressure drop that depended on air flow rate but not on downstream vacuum, regulating automatically the air to fuel ratio with sufficient precision.

In the following years other improvements were introduced in carburetor design, with the aim of keeping the air to fuel ratio constant in all operating conditions. In

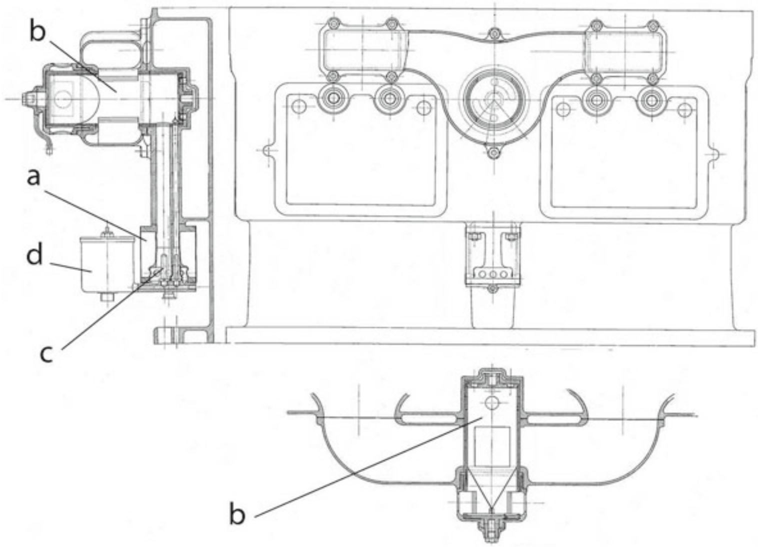

Fig. 4.23 In jet carburetors the air and fuel mixture is built up by spraying gasoline in the air stream. Air was sucked through an intake and a regulation valve close to the intake manifold (courtesy of FIAT)

particular the ratio tended to be leaner when the engine was cold, because of fuel vapor condensation on the walls of the intake manifold and ducts. In addition, fuel droplets in the air stream tended to aggregate in larger drops during sudden manifold pressure rise, as for instance in acceleration; larger drops burned only partially with an effect similar to leaning.

The first problem was solved by adding a second throttle valve upstream of the restrictor. This valve, called *choke* or *starter*, increased vacuum significantly causing an additional quantity of fuel to be sucked up by the engine. After the engine had started, the choke valve had to be opened gradually until a correct engine operation was obtained. The mixture leaning during sudden transients was avoided by installing a simple injection pump, operated by the throttle valve motion and sensitive to opening speed.

Since the application of a carburetor introduced an unavoidable additional pumping loss, in high performance engines multiple carburetors were installed, with a carburetor per cylinder in race engines. In some commercial engines with improved performance two (for four cylinder engines) or four (for eight cylinder engines) carburetors were integrated in a single body, the so-called multiple barrels carburetors.

Electronically controlled fuel injection systems that were introduced in the 1970s solved radically all the regulation problems that still affected mechanical carburetors.

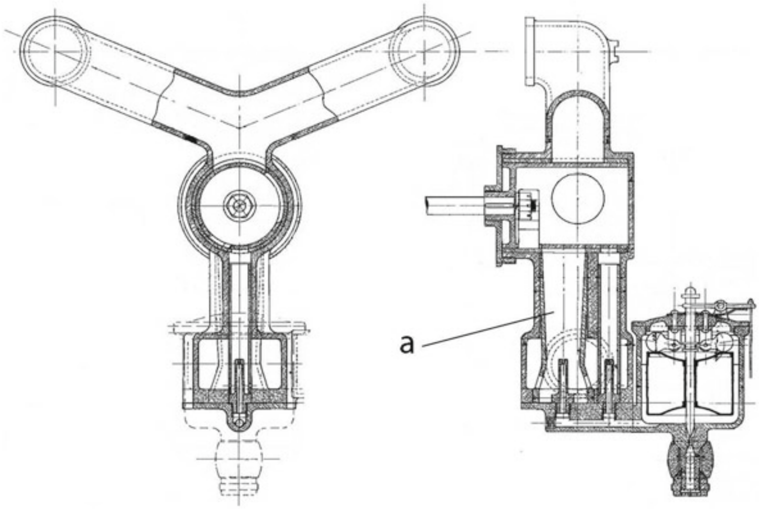

Fig. 4.24 The restrictor in the carburetor barrel, shaped following the geometry defined by Venturi in 1780, caused a local pressure drop depending on air flow rate only and not on downstream vacuum with an automatic regulation of the air to fuel ratio (courtesy of FIAT)

4.2.4 Lubrication

A basic problem in internal combustion engines has always been the lubrication of the many rotary (as crankshaft bearings) or sliding (as cylinder liners) couplings subject to wear. A solution to this problem, widely applied in the early engines, was to install oil dispensers close to the most critical points, such as connecting rod bearings, crank shaft bearings, cylinder liners, etc. These *oilers* were provided with a glass reservoir, to be easily inspected, containing a quantity of oil that was dripping into the coupling, as shown in Fig. 4.25a. Taps were provided to adjust oil leakage to the correct value and to avoid leakage when the engine was stopped.

A glass window (T in the figure) allowed the user to count the drops of oil released in a given time; user manuals reported the oil rate desired with reference to operation conditions; all oil was wasted after lubrication. This very simple system was improved by installing a single oil tank, usually on the dash board, with many outlets to the different lubricated points; each outlet was provided with a regulation tap and an inspection window.

It could be useful to remember that nobody drove alone without the assistance of a second driver or a mechanic, taking care of all auxiliary operations such as lubrication, fuel pumping, etc.

These central dripping lubrication systems were improved further, by introducing an automatic feed pump from an oil tank and by applying a suitable piston pump to each oiler, to adjust the oil rate to the optimum value automatically. Each pump was operated by the engine itself, from the cam shaft as in the example in Fig. 4.25b with

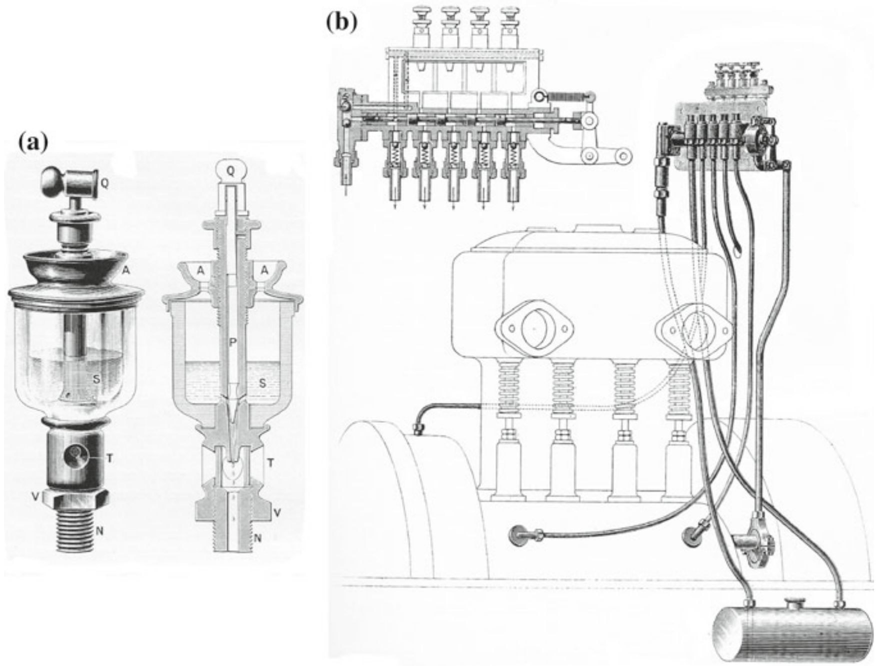

Fig. 4.25 **a** Oilers used in the early engines were made by a glass reservoir (S), to be easily inspected, containing oil dripping into the coupling. Taps (Q) were provided to adjust oil leakage to the correct value. **b** Drop lubrication systems were improved by introducing an automatic feed pump from an oil tank and by applying a piston pump of suitable size to each oiler (redrawn from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

the double advantage of proportioning the lubrication rate to the engine speed and to interrupt lubrication when the engine stopped.

The next step, in the 1910s, was applying a closed lubrication circuit, where oil was reused after leaving each lubrication point; engines were closed by a lower cover, the *oil sump*, where the oil leaking from the engine was recovered and contained. The oil was splashed to each lubrication point by engine cranks diving into the oil sump; oil pockets were provided in the engine block, storing oil temporarily, to compensate for changes of oil level in the sump, due to accelerations (acceleration, braking, driving in a curve or on a slope). An example of this practice is shown in Fig. 4.26.

The final improvement, introduced in the 1930s, was to distribute oil in the closed circuit by suitable tubes provided in the engine block and head; the lubrication circuit was under pressure to increase oil lift in bearings and to allow oil distribution in any operating condition. Gear oil pumps have been used almost always for this purpose until now.

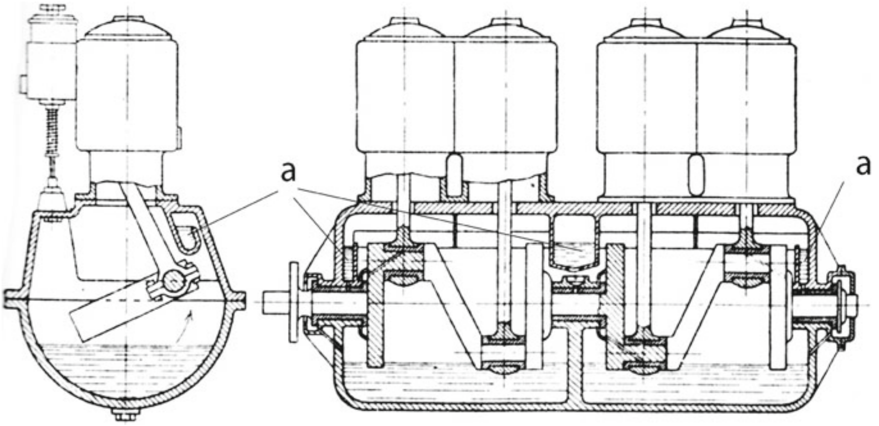

Fig. 4.26 In early closed circuit engines, oil was splashed to each lubrication point by the engine cranks diving into the oil sump; oil pockets *a* were provided in the engine block to store oil temporarily, to compensate for the change of oil level (from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

4.2.5 Ignition

It is possible to classify the many different ignition systems developed for internal combustion engines in three families according to how combustion was started:

- electric spark;
- hot spot;
- continuous flame.

It would be wrong to think that present electric spark systems were the final choice after years of development of different solutions. As a matter of fact there was an immediate convergence of all engine inventors toward electricity: The 1807 De Rivaz engine had an electric ignition as well as the 1854 Barsanti and Matteucci engine. The basics of the electric spark had been studied by Alessandro Volta in his experiments on electric ignition of hydrogen mixtures, dating back to 1775.

The so-called Volta's gun demonstrated that an electric spark was suitable to ignite a hydrogen mass and produce a quantity of energy suitable to launch a bullet; the following development of De Rivaz and Barsanti demonstrated that with a suitable machine it was possible to control the release of this energy and produce usable work.

Nevertheless, different ignition systems were proposed and developed, because of the difficulty in producing and distributing electric energy on board of the early vehicles. Electric energy is in theory easily transportable and can be easily controlled by switches. This fact was particularly appreciated to ignite the combustion in connection with the crankshaft position and electric switches were suitable components to have engines working automatically.

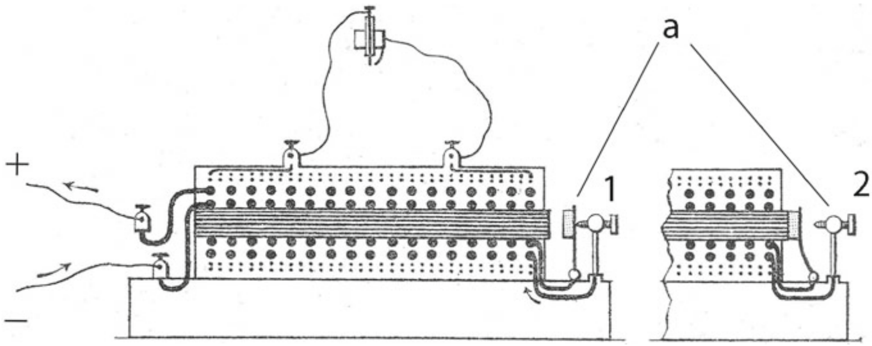

Fig. 4.27 In a Rühmkorff's coil the continuous electric current generated by a battery was conveyed into an electric coil wound around an iron core; the magnetic force in the iron core attracted the moving part *a* of a switch interrupting the electric current (redrawn from Baudry de Saunier 1905)

The first electric ignition systems used a device similar to the Rühmkorff's coil. According to its inventor, the continuous electric current generated by a battery was conveyed into an electric coil wound around an iron core (Fig. 4.27); the magnetic force, generated in the iron core, attracted the moving part of a switch *a* (1 switch closed, 2 switch opened), interrupting the electric current. Current interruptions released the switch, thereby feeding the coil again. The result was a chopped current into the coil.

A second coil with a larger number of turns, wound around the first, supplied a chopped current at higher voltage suitable to deliver sparks at an electrode. A typical Rühmkorff's coil, also called *vibrator* by engineers, because of its way of operating, is shown in Fig. 4.27.

Vibrators worked continuously generating a high voltage; the spark electrode was connected to the electric circuit when the intake phase of the air and hydrogen mixture was completed. However, this way of producing and conveying electric energy, developed in the 1850s, was more suitable to physics laboratories than to industrial machinery; this was the reason why the ignition system used in Otto atmospheric engines was a continuous flame, burning the same lighting gas used as engine fuel.

A valve system had to convey this continuous flame periodically, with a suitable timing, to the combustion chamber, avoiding exhaust gases blowing through the same duct extinguishing the flame. Such a system was considered to be unsuitable to a moving engine where air motion could easily affect its operation.

For this reason, Daimler, still thinking that electricity was unsuitable, decided to use a hot spot ignition. A lamp, fed with the same liquid fuel used for the engine, heated a metal pin mounted in a hole through the cylinder wall to glowing temperature. The pin had one end facing the flame, while the other was facing the combustion chamber. The lamp had to be used only for a while, after engine cranking, because the combustion heat itself could keep the pin in glowing conditions. The pin started

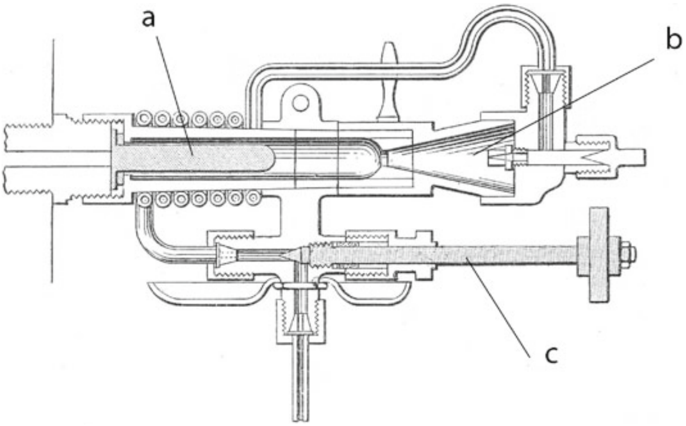

Fig. 4.28 A hot spot ignition system: the glow pin *a*; the small burner *b* and the manual valve *c* for fuel regulation are shown (redrawn from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

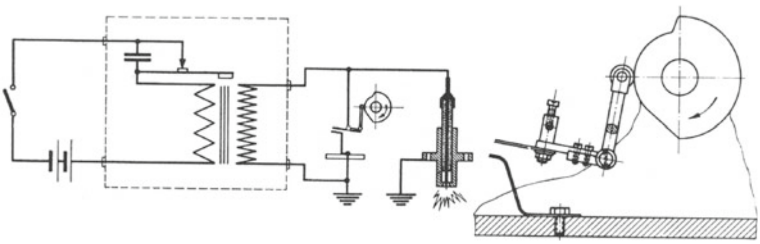

Fig. 4.29 Electric ignition system used in the 1886 Benz automobile engine (from L. Morello, *Evoluzione tecnologica dei motori automobilistici ad accensione comandata*, ATA: Ingegneria dell'autoveicolo, 2004, N° 7/8 e 9/10)

combustion as soon as compression had brought the mixture to the self combustion temperature.

A similar system is described in Fig. 4.28; the glow pin *a*; the small burner *b* and the manual valve *c* for fuel regulation are shown. The fuel is fed to the device by gravity. The advantage of this system was its simple layout and high reliability, the main disadvantage was the impossibility of adjusting the spark advance to a suitable value.

One of the first automotive engines made in 1886 by Benz used instead an electric system, similar in principle to that used by Barsanti and Matteucci; a scheme of the electric circuit and a detail of the rotary switch operated by the engine is shown in Fig. 4.29.

At the end of the 1910s the electric spark ignition was applied almost by all manufacturers; the differences between the different systems was how the electric energy was generated and managed.

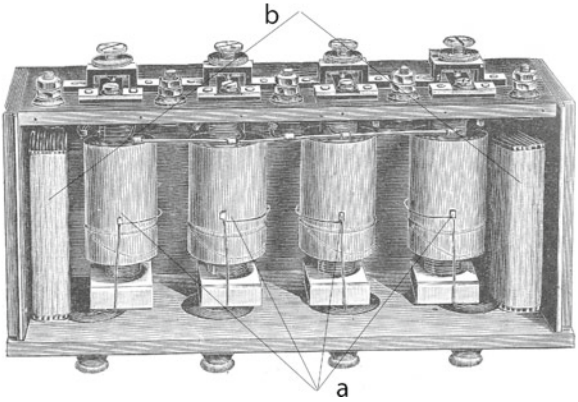

Fig. 4.30 Electric ignition system for a four cylinder engine, with four vibrators *a* and two batteries *b* (redrawn from Baudry de Saunier 1905)

Four different systems can be identified:

- vibrator ignition;
- low voltage magneto ignition;
- high voltage magneto ignition;
- breaker ignition.

The application of a manual advance adjustment was a feature common to all systems: The driver had to adjust the advance using certain empirical procedures, like setting a low advance during cranking, to avoid engine counter rotation; advancing the ignition after start to the highest possible value, to improve performance, but avoiding *knocking* (detonation).

In the first already described solution, electric energy came from lead-acid batteries that had to be recharged at home from time to time. Figure 4.30 shows an electric ignition system for a four cylinder engine. The fact that the source of energy was depletable was considered a major drawback; this system was abandoned for a time until suitable electric generators were available to recharge batteries during engine operation; but the relevant cost increase could be accepted only after other electric appliances had to be added on board of vehicles.

Magnetos were considered as simple electric generators able to supply the current necessary for ignition. The low voltage version of this electric machine was simply a set of coils put in rotation inside a continuous magnetic field; the current collected by sliding contacts was suitable, with simple transformations, to generate the spark. Figure 4.31 shows two different versions of a low voltage magneto: The magnetic field was generated by a set of horseshoe permanent magnets, for instance two (a), or a two poles rotor spinning inside the magnet (b) had a suitable number of coils that had to be insulated electrically.

Wire insulation, today easily made by immersion of the copper wire in a synthetic resin, was initially made by winding a silk thread around the copper; small displace-

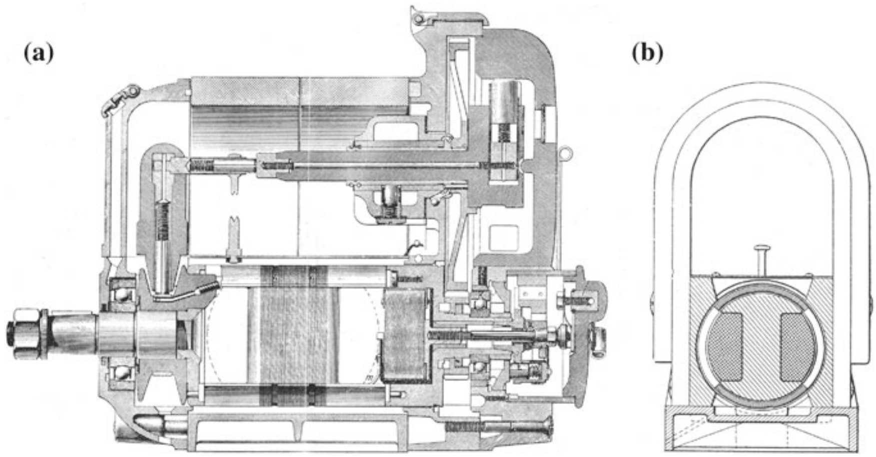

Fig. 4.31 Two versions of a low voltage magneto; a rotary coil version (**a**) and a fixed coil version (**b**) (from Baudry de Saunier 1905)

ments in the silk thread caused electric contacts with local short circuits reducing the output voltage. For this reason the voltage could not be high enough to make an electric spark with sufficient energy directly available.

Two sliding contacts were provided, one axial, at right, one radial at left; the radial contact connected with as many circuits as the cylinders in the engine, while the axial contact closed the electric circuit, usually using the steel mass of the engine and the chassis as return circuit. The multiple output of the magneto could be rotated for advance adjustment; the magneto was rotating at half the speed of the engine for correct timing.

To avoid one sliding contact, some magnetos had a fixed coil while a rotary iron element was provided to generate the necessary periodic magnetic field variation, as shown in the figure at right.

The voltage increase necessary for sparks was obtained by opening switches and by utilizing the voltage peak generated by the circuit inductance. These switches were directly installed inside the combustion chamber; their contacts were closed in short circuit for all the time but at the time of spark.

Figure 4.32 shows one of these switches; they were opened by additional cams on the camshaft with a profile suitable for very quick opening. Since magneto speed was not enough for firing during hand cranking, sometimes additional vibrators were provided that were switched off after the engine had started.

In high voltage magnetos an additional secondary coil was placed around the primary rotating coil, having the function to increase the voltage. High voltage magnetos were connected to conventional fixed electrode spark plugs, but this obvious solution was available only after copper insulation could be improved.

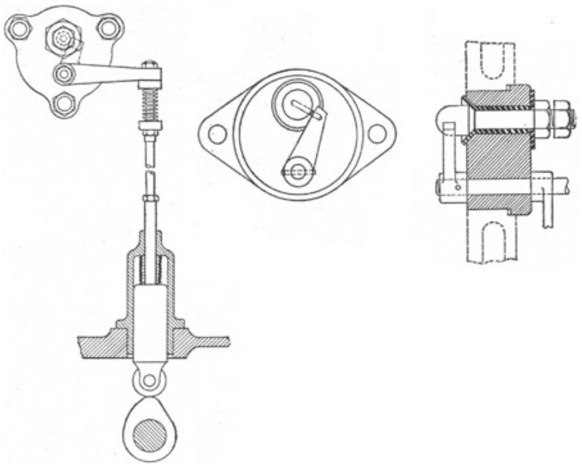

Fig. 4.32 Ignition switches were directly installed inside the combustion chamber; their contacts were closed in short circuit for all the time but at the time of spark (courtesy of FIAT Historical Archives)

Charles F. Kettering of DELCO patented in 1908 the first ignition system operated by a battery, recharged on board of the vehicle. Systems of this kind were in use till the 1970s when electronically controlled ignition systems were introduced.

The *breaker* (switch), controlling the current transient in the coil, is placed in the low voltage circuit, fed by the continuous current generated by the battery. The breaker is no longer a vibrator, but is operated by the engine with a cam, generating a contact at each second turn of the crankshaft. A condenser reduced the temporary peak of voltage, to avoid too strong sparks from damaging its electrodes. Spark plugs were connected to the high voltage circuit of the coil by a distributor, switching the contact on each cylinder.

A major improvement consisted in an automatic device controlling the spark advance as a function of engine speed and manifold pressure. This device could rotate the switch with a centrifugal regulator and a pneumatic actuator.

4.2.6 Starters

In the early electric ignition systems electricity was provided by dry cells; they produced electricity through an irreversible chemical reaction that made the cell unusable when discharged. An improved system included batteries to be recharged by connecting them to the home electric network. Lead-acid batteries, reusable many times, were invented by Plante in 1859. They were made by rolling up thin sheets of lead with separators made by a porous and insulating material. This roll was placed in an insulating jar, containing a diluted solution of sulfuric acid.

A battery like this had to be charged and discharged for many times before the porous spacers could contain the suitable mass of lead oxide, necessary to store the desired quantity of energy; this technique was expensive and inefficient.

Foure improved the lead battery design in 1881, by developing a battery where electrodes were made by lead grids with their mesh full with lead oxide paste. According to this design, flat electrodes were piled up with insulating separators in between, to obtain the desired voltage. The fabrication time of the battery was reduced because the lead oxide could be obtained by a separated process, not including electrolysis.

Each pair of plates could generate a voltage of about 2.25 V; more plates in a stack, connected in series, could deliver the desired voltage while more stacks in parallel could generate the necessary amount of current.

Almost immediately, batteries with a voltage of about 6, 12 and 24 V were standardized; 6 V batteries disappeared in the 1970s because their low voltage made high currents and consequently heavy copper wiring necessary, while 24 V were used only on large industrial vehicles. This kind of battery is still in use today, with some improvements, as service batteries of internal combustion engines for vehicles.

A contribution to lead acid batteries diffusion on cars was made in 1912 by the first application of an electric starter; also this invention was made by Kettering, under request of Leland, President of Cadillac at that time. Rumors say that Leland was impressed by the death of one of his friends, due to injuries he suffered while hand cranking his automobile.

Before the invention of electric starters engines were started manually by a hand crank connected to the engine crankshaft; the joint between the crank and the engine shaft was made by front teeth with asymmetric profile, designed to disengage as soon as the engine was started.

But the driver had to perform other complex maneuvers before engine cranking. The first step was mixture enrichment, if the engine was cold. This purpose was accomplished in earlier engines by introducing in the cylinders close to firing a suitable quantity of gasoline; each cylinder had a tap on its top with a little funnel for this purpose (see for instance Fig. 4.11). In more recent engines the enrichment function was accomplished by a choke valve in the carburetor.

The second step included manual spark advance adjustment; the purpose of this adjustment was to avoid slow combustion in the cold engine from taking pace too late, at open exhaust valves, and preventing the engine from starting backwards due to an early ignition.

At this time the engine could be cranked. Cranking required a strong effort, particularly in large displacement engines and many would-be drivers were discouraged by this operation. In addition, an unsuitable spark advance adjustment could start the engine backwards, sometimes causing severe injuries to the operator since the crank joint could not disengage in counter rotation.

Electric starters were therefore a welcome simplification that made larger distribution of the automobile possible, but the introduction of the starter motor required suitable batteries and current generators to be installed.

The system that Kettering developed was based upon the concept that a single electrical machine could either work as starter or as generator; this is in theory

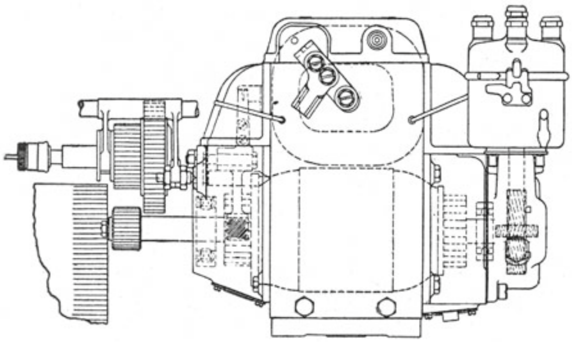

Fig. 4.33 Kettering's electrical machine includes a suitable gearbox that can engage with two different transmission ratios; the first, about 1:1, to generate current, the second 1:100, for engine starting (from L. Morello, *Evoluzione tecnologica dell'impianto elettrico*, ATA: Ingegneria dell'autoveicolo, 2008, N° 1/2)

possible because the two machines can be mechanically identical. In practice, engine starting requires high torque and, consequently, high currents at low speed, while current generation, in normal working conditions, requires a much lower current to recharge the battery, involving lower torque at higher engine speed.

This problem was solved by Kettering in a straightforward way, with a suitable gearbox that could engage the electrical machine with two different transmission ratios: About 1:1, to generate current and 1:100, for engine starting. A drawing of this machine, integrating also the distributor and the ignition breaker, is shown in Fig. 4.33. The electrical machine had two different windings and blade collectors, connected in series and in parallel, in consideration of the different current values. The mechanical engagement with the flywheel for engine starting was made by operating a dedicated pedal.

Later, generator and starter functions were obtained by separate electrical machines, since the added cost was paid off by avoiding a gearbox. However, the very large range of speed of the generator was difficult to be accepted. In fact, designing the generator to charge the battery at high engine speed, caused the battery to discharge at low speed, during city driving. On the contrary, designing the generator to charge the battery at low speed, caused too high a voltage at high speed: A voltage regulator was required.

A mechanical regulation was initially applied. Figure 4.34 shows a centrifugal regulator that disengages the generator when a speed threshold is overcome. In this system, the generator is able to recharge the battery at low engine speed, but it is stopped at high speed.

Later, electrical regulators were applied. Two alternatives were considered: Continuous and on-off regulators. An example of the first alternative was Kettering's centrifugal rheostat, controlling the generator excitation current to a suitable value, to avoid battery overcharging. The most common on-off solution included a set of three relays. A minimum voltage relay operating when there was a danger of

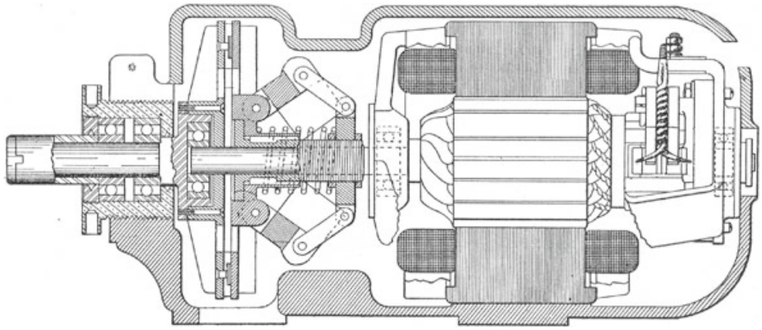

Fig. 4.34 Generator with mechanical regulator: The generator is disengaged when a speed threshold is overcome (from L. Morello, *Evoluzione tecnologica dell'impianto elettrico*, ATA: Ingegneria dell'autoveicolo, 2008, N° 1/2).

discharging the battery, because of too low generator voltage; a maximum current relay and a maximum voltage cutoff relay that interrupted battery recharge beyond a safety value.

The alternator, applied since the early 1970s, simplified the regulation being less sensitive to the speed; in this case a set of solid state diodes converted the alternate current to direct current.

4.3 Gearboxes

A gearbox with a clutch, or a start-up device of other kinds, are essential for adapting the transmission ratio between engine and wheels to the needs of the vehicle and the characteristics of the engine. This transmission ratio should be very high, ideally infinite, at vehicle start-up.

In the early cars, the gearbox was confused with a device for speed adjustment: The term of *speed* to name a given transmission ratio comes from this misinterpretation.

4.3.1 Manual Gearbox

Patent documents of 1784 give evidence that Watt foresaw the use of a constant mesh gear box, with dog clutches, to improve the traction performance of a steam engine; it is rather difficult to demonstrate how this idea might have influenced the design of cars, which did not follow this scheme indiscriminately.

The first commercialized internal combustion engine cars are, without doubt, a result of the efforts by Benz and Daimler in 1885 and 1886 , and the transmission problem was solved by using a scheme completely different from that proposed by Watt.

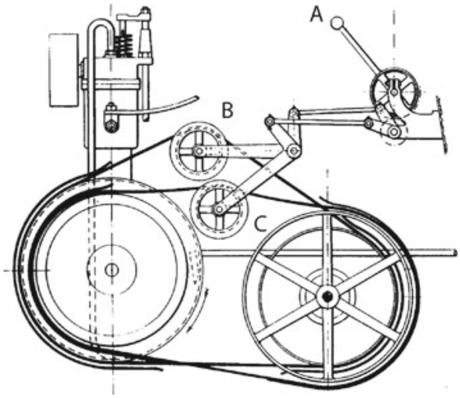

Fig. 4.35 Complete transmission of the 1885 Daimler car. Two transmission ratios are available, using a leather belt transmission. The slipping of the belts is exploited to start-up the car (redrawn from Genta and Morello 2009)

The complete transmission of the Daimler car is shown in Fig. 4.35. Two different transmission ratios are obtained using leather belt transmissions with pulleys of different diameter. The belts are always wound on their pulleys, but the motion is transmitted by only one of them, when one of the two tensioners *B* (for the high speed) and *C* (for the low speed), operated by the control stick *A*, engages the corresponding belt. Belt slip, occurring when the tensioner is not completely engaged, is exploited to start-up the vehicle from a standstill.

In this case the driveline design is simplified due to the lack of wheel suspensions. Many improvements to this layout were used in the following Benz car. The two speed transmission was inspired by the power transmission in contemporary workshops, where a single steam engine or water wheel operated a number of working machines through belts. This kind of transmission was probably invented by Anderson in 1849.

The two driven pulleys (in the top view in Fig. 4.36) are coupled with as many idling pulleys (at the outboard of the driven pulleys); the latter have a slightly smaller diameter than the driven pulleys and the active cylindrical surface of the driven pulleys is rounded to match the active surface of the idle ones. The two driving pulleys (in the back of the car, aligned with the engine crankshaft) have an adequate width to bear the belt on both driven and idling pulleys. Two tensioners can shift the leather belts from matching the driven pulleys to matching the idle ones.

The belts are crossed in order to increase the winding angle on the pulleys; belt tension is adjusted periodically, by changing the distance of the center lines. The rounding on the surface of the driven pulleys makes belt shifting easier; the lower diameter of the idling pulleys decreases the tension of the belts when they are not working, making the time between two subsequent tension adjustments longer.

The start-up function is again performed by exploiting belt slip; the suspension motion of the driving wheels is compensated for by two chain transmissions that connect the driven pulleys with the rear wheel hubs.

The literature on these and other cars of this time did not suggest a sequential use of gears to accelerate the car, but the car could be started in either one of the gears,

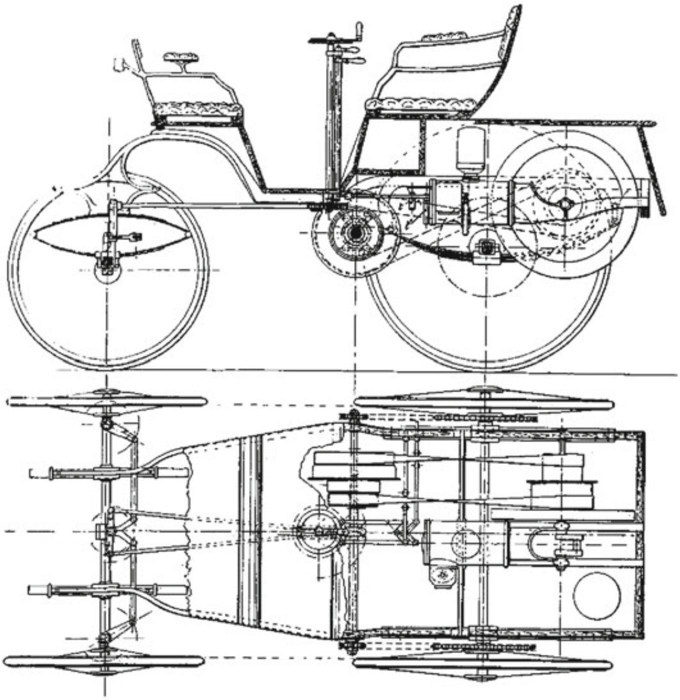

Fig. 4.36 Two speed transmission of the 1886 Benz car, of the leather belt type. Two tensioners can shift belts from a position engaged with a driving pulley to that engaged with an idling pulley (redrawn from Genta and Morello 2009)

and the choice depended more on the desired cruise speed than on the traction force needed for starting.

The idea introduced by Watt was then applied to the next generation of gearboxes. This is usually noted by saying that the first cars demonstrated how the technical skills of their inventors were polarized on engines, sometimes neglecting the other achievements that had been already obtained in the contemporary state of the art. This fact could be also explained by the difficulty of exchanging ideas within the technical communities of different countries.

A typical example, similar to contemporary layouts, is reported in Fig. 4.37, where a drawing of the FIAT 8/16 HP of 1902 is shown. This gearbox features three speeds and a reverse; in the oldest cars the reverse gear was missing.

The engine rotates the lower shaft, at the left, in the view showing a longitudinal cross section of the gearbox. This gearbox has a single reduction stage, where all driving gear wheels are aligned on the input shaft and all driven wheels on the output shaft. On the engine side the reverse gear is first, followed by first, second and third gears. An idle gear wheel, used to reverse the rotation speed of the output shaft is visible on the cross section.

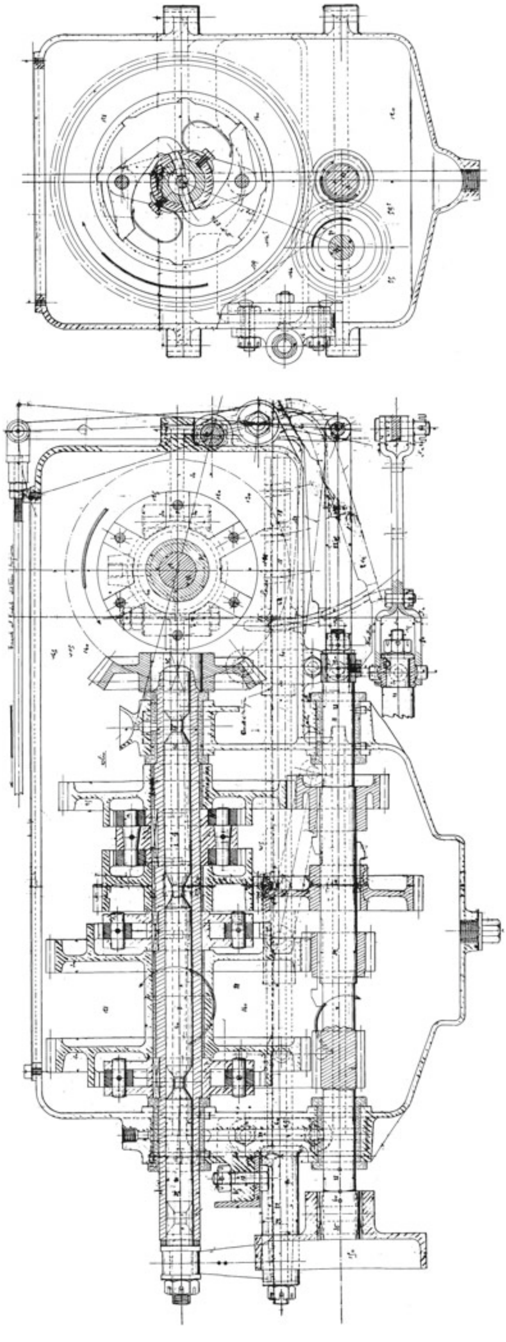

Fig. 4.37 Single stage, three speed gearbox of the FIAT 8/16 HP of 1902. The internal shifting mechanism is made by a cylindrical rod, mounted inside the driven shaft (redrawn from Genta and Morello 2009)

Driving wheels always mesh with driven wheels and must, therefore, be free to rotate on the output shaft. The output shaft operates a bevel gear, which moves two shafts through a differential. These are coupled through drive chains to the rear driving wheels, according to the scheme already seen in previous figures.

A tapered friction clutch, not represented in this figure, allows start-up of the vehicle and separates the gearbox from the engine during gear shifts (see for reference Fig. 4.45).

Three new mechanisms not yet introduced are here present: The reverse gear, the differential and the friction clutch. Their origin is for sure older than this car: The reverse gear was introduced by Selden in 1879, the differential by Pecquer in 1827 and the tapered friction clutch by Marcus in 1885. During the first years of the century these three mechanisms were integrated in a transmission suitable to automotive application.

The gear shifting mechanism is rather sophisticated, made by a cylindrical rod mounted inside a cavity in the driven shaft that can be moved axially. This rod shows some annular indentations, which in certain positions allow two ratchets to engage with the driven wheels; the detail of the reverse gears ratchets can be seen in the cross section.

When one of the grooves faces a pair of ratchets, two leaf springs provide their engagement with the ratchet gear; when the rod is shifted, ratchets retract, leaving the wheel again idle. The position of the grooves is operated by a sequential shift stick, where the positions of reverse, first, second and third follow each other.

This kind of gearbox architecture (*constant mesh gears*) was applied to many cars of that era, but was soon abandoned because of its complexity and consequent fragility. The next scheme is that of *sliding gear trains* (*trains balladeurs*, in French).

Sliding trains gearboxes can be exemplified by the FIAT 60 HP car of 1904, whose gearbox is shown in Fig. 4.38. This invention is older than its automotive applications since it was designed by Griffith in 1821 for workshop machinery.

It is not the first time that a better performing architecture (constant mesh) is abandoned in favour of a less evolved alternative (sliding trains), because a particular component (the dog clutch, the synchronizer, in this case) has not been developed yet. Sliding trains will soon be abandoned again, in favor of constant mesh, when the technological improvements made it possible.

The gearbox of Fig. 4.38 is still of the single stage type and has four speeds plus a reverse speed; gear wheels, grouped in two trains, from the first to the fourth, can slide on the upper driving shaft. The engine (not shown) is on the left, while on the right the bevel gears operating the pinion of the chain transmission through the differential can be seen.

The first and second speed wheels are located on the first train, while the third and the fourth speed wheels are on the second; these trains are mounted on a part of the shaft with a square cross section that allows them to turn with the shaft, being free to shift along it. Train sliding is accomplished by suitable sleeves that bring one wheel at a time to engage with its counterpart; the gears mesh only when their correspondent gear is selected.

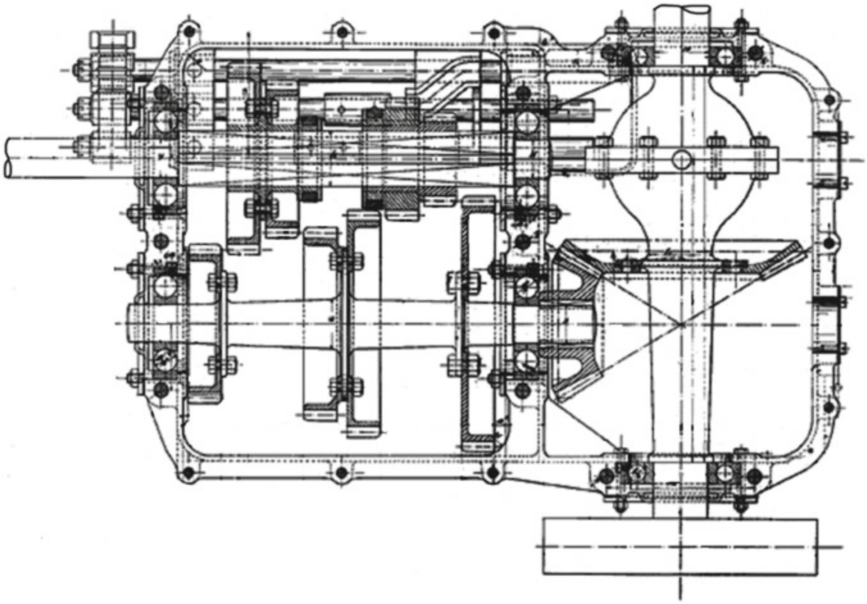

Fig. 4.38 Sliding train gearbox with four speeds of the FIAT 60 HP of 1904. The two gear trains are made by the driving wheels of the first and second speed and by those of the third and the fourth speed (redrawn from Genta and Morello 2009)

Reverse speed is obtained using a train of idler gears only, not represented in this figure, meshing with the first speed gears, when their train is in the idle position.

The sleeves are moved by forks fixed to sliding rods, partially visible under the gearbox shafts; there are two rods for moving the train for the first and second speeds and that for the third and fourth speed, while an additional rod is dedicated to reverse.

This kind of layout created the need for a particular kind of control stick, where gear shifting is no longer sequential, but is characterized by two separated motions: one across, to select the train to be engaged, the second, longitudinal, to engage a specific gear. This layout consolidated in common practice, surviving unchanged in our contemporary cars.

Sliding train gearboxes required a particular skill from the driver, who had to synchronize the wheels by means of the engine during idling, before engaging the next gear (double clutching); an imperfect maneuver was accompanied by the noise due to scratching of the gears getting in contact at an inappropriate speed.

Some manufacturers improved this architecture, actually returning to the Watt's idea of constant mesh gears; to show this new layout, the drawing of the gearbox of a small truck of the end of the 1910s is reported in Fig. 4.39.

In this gearbox three speeds are available together with a reverse speed; the gearbox is connected to the engine on the right of the figure, while the output flange is on the left. The flywheel on the output shaft is not part of the engine, but is the drum

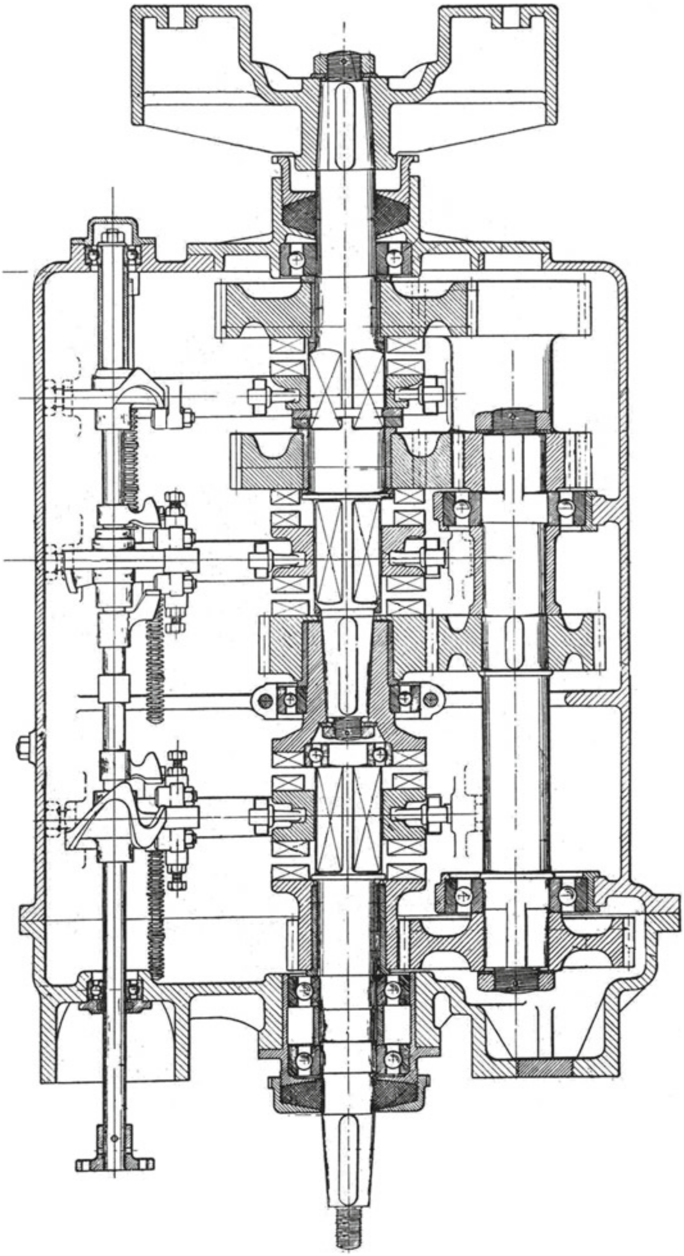

Fig. 4.39 Dog clutch gearbox of a truck built in the 910s. Sliding trains are now reduced to small front tooth gears working as clutches (redrawn from Genta and Morello 2009)

of the transmission brake. The input and output shafts are now coaxial; this layout is appropriate to the application of a universal joint transmission, that started to be applied in these years. Gear wheels are always meshing and carry dog clutches at their sides and the sliding trains are now reduced to the pairs of dog clutches.

The scratch problem is not solved, but possible damages are localized on an auxiliary component, the dog clutch, that can be sacrificed, with smaller impact on the operation of the gearbox. Dog clutch teeth can also be rounded, making shifting easier, without penalty for wheel size.

Input and output shafts are coaxial, the upper shaft made in two parts, free to have different rotation speeds. The lower sliding train can alternatively engage the two parts directly (third speed) or move a third shaft (*countershaft*), located at the right in the same figure. With this dog clutch only engaged it is possible to obtain the first and the second speeds, using the second train in the figure; with the last train it is possible to engage the reverse speed, connecting the countershaft to the output shaft and then to a pair of idlers (in practice a second countershaft), partially visible on the right of the figure.

Sliding train motions are operated by front cams, that allow in this case sequential control. A similar architecture, but for the control, is still present in front engine, rear wheel driven vehicles.

However, at that time these technical solutions were not consolidated and, as often occurs at the dawn of a new technology, deviations from what we consider is the main evolutionary path were many. After the engine, the gearbox was the field where early automotive engineers concentrated their innovative efforts.

A comprehensive classification of all the solutions that were attempted is well outside the scope of this section, even limiting the discussion to manual transmissions and only those that could be considered as the most original solutions are here considered.

Between 1924 and 1938 Frazer Nash built in England different cars, all with sport performance but affordable price in their category. Essential to these cars was the driveline, shown in Fig. 4.40. The gearbox is made by chain transmissions, three for forward speeds, one for reverse speed. Driving chain wheels (at right in the drawing) are operated by a bevel gear box, connected to the engine; this bevel gear box includes no differential gear. On the right half of this intermediate shaft the sprockets for the first and the reverse speed are located; on the left half shaft there are the sprockets for the second and the third speed.

Notice the idler reverse system with chain and gears. Driven wheels are directly mounted on the rear one-piece shaft; they can be moved along their shaft for chain alignment. A chain transmission was also used for compensating for suspension motion. The wheels were engaged by simple dog clutches.

The lack of a differential made the car difficult to drive, but very manageable for an expert driver on unpaved roads, common at those times. Admirers of these cars extolled the easy road holding, the excellent gearbox maneuverability and the ease with which broken parts could be replaced in the transmission.

A car with different technical details, also original and uncommon, is the 1907 Sizair Naudin, also known for featuring one of the first independent suspensions. Here

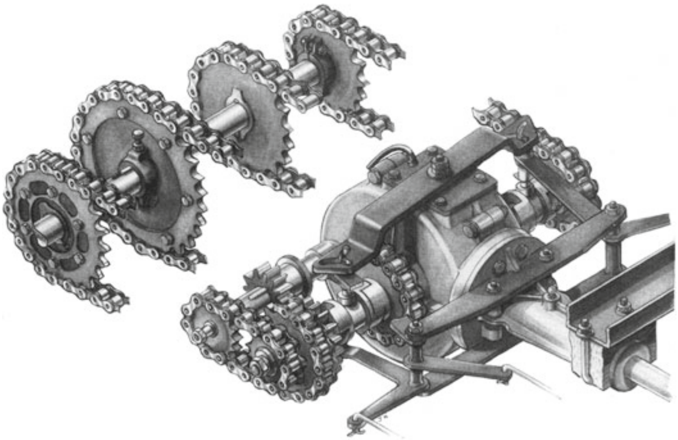

Fig. 4.40 Frazer Nash gearbox of 1924, made by chain transmissions. Three speeds and a reverse were available (from Genta and Morello 2009)

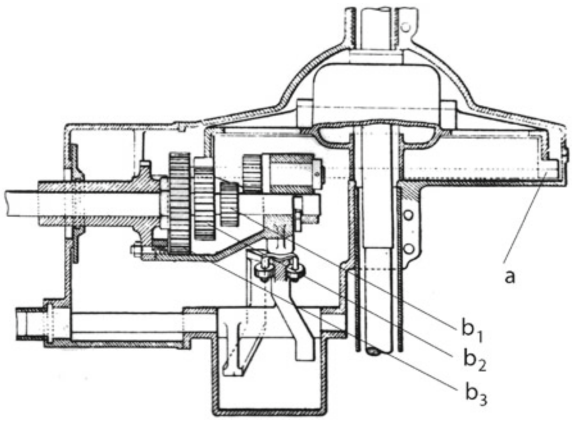

Fig. 4.41 Sizair Naudin gearbox of 1907. This design can be assimilated to a sliding train gearbox, with bevel gears (redrawn from Genta and Morello 2009)

the design goal should have been to contain gearbox cost, or at least the number of gear wheels, at that time quite expensive.

The gearbox architecture shown in Fig. 4.41 can be assimilated to a sliding train gearbox. There is a single driven wheel, the crown gear a. The only sliding train, made by spur gear wheels b_1, b_2 and b_3, is installed on a bearing swinging around the lower shaft in the drawing; the swinging motion of the bearing is necessary to mesh the driving wheel in use with the crown gear at different distances, depending on the driving wheel diameter.

The swinging motion of the driving shaft is compensated for by a universal joint transmission between engine and gearbox. The cam at the bottom of the drawing

combines shift and swing motions and bears gearing forces. Bevel gears should have been used instead of the spur gears, for correct matching; teeth shape is, nevertheless, approximated by a cylindrical shape, with consequent contact errors. The reverse idler is also present on a dedicated shifting train.

A last example of amazing engineering ingenuity is given by the 1904 Turicum (a Swiss automotive trademark) shown in Fig. 4.42, with a drawing of the complete chassis: Here one of the earliest continuously variable transmissions used on automobiles can be seen.

The motion is transmitted to the rear axle by two friction wheels *a* and *b*, the first made of solid iron, the second with a rubber tread on its rim. The wheel *b* is connected to the shaft *c* through a spline and groove, that allows the wheel to be shifted along the shaft; the shaft *c* rests on a swinging bearing *d* and allows wheels *a* and *b* to be pressed against each other by the spring *e*.

By pulling the lever *f* it is possible to change the contact point between the two pulleys, between the center of the wheel *a* (infinite transmission ratio: transmission idling) and its rim (transmission ratio about 1:1). In the idle position, the friction is eliminated by unloading the spring *e*; the slip between the two wheels is used to start the vehicle up.

The proposals above were not imitated by other manufacturers and were probably abandoned by their own inventors. The evolution of manual gearboxes concentrated on perfecting a countershaft or double stage architecture, that became universal on all cars with front engine and rear drive.

An example of this evolution is offered by the gearbox of the FIAT Balilla of 1934 (four speed version, the first gearbox of this car in 1933 was a three speed design) shown in Fig. 4.43. This gearbox shows two different sections: The rear, for the first, second and reverse speeds, features a sliding train with cylindrical straight teeth. The front features helical gears (always meshing) and synchronizers.

This compromise was justified by the high cost of synchronizers, considered high technology components at that time. Synchronizers were limited to the more frequently used speeds, which could also benefit of helical gears, with gearing noise reduction.

Earlier engineering manuals suggested, as a good practice, to design the top ratio (in this case the final differential ratio) with values slightly higher then those ideally needed; this rule was addressed to limiting the number of gearshifts necessary to maintain the car at cruise speed, and demonstrated the difficulty for drivers to change speed with sliding train gearboxes. It is thus possible to assume that synchronizers brought benefits not only in shifting quality, but also in noise and fuel economy.

The gearbox of the FIAT 1400 of 1950, shown in Fig. 4.44, has, like many cars of this time, synchronizers on all speeds but the first, again for reasons of economy; the first is included in a sliding train mounted on the sleeve of the third and fourth speeds. The reverse speed is obtained with an idler, not shown in the picture, meshing with the wheels of the first gear when they are in neutral position.

During the following period, synchronizers were improved and made less expensive thanks to higher volume production; since the 1970s also economy cars had synchronizers on all speeds.

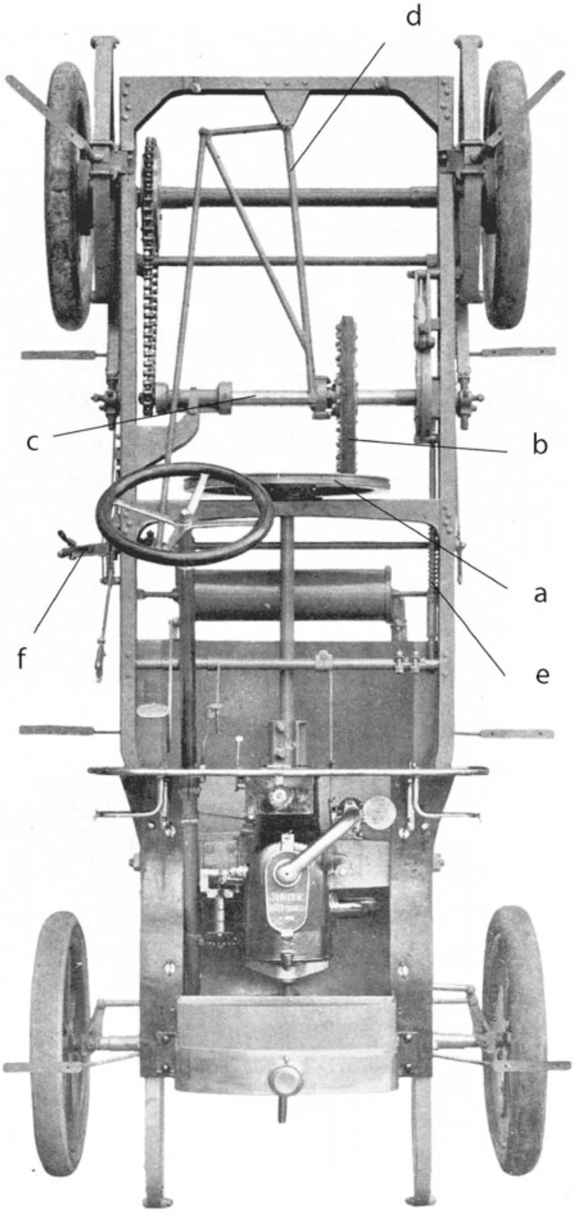

Fig. 4.42 Turicum chassis of 1904; A continuously variable transmission based upon two friction discs *a* and *b*, where the first is made of solid iron and the second has a rubber thread to improve contact friction, can be seen (redrawn from Genta and Morello 2009)

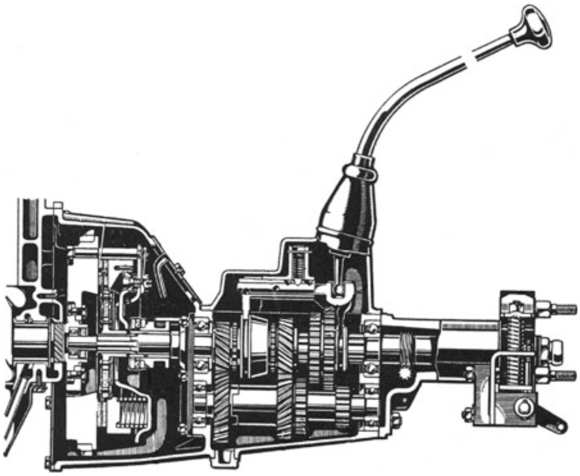

Fig. 4.43 Four speed gearbox of the FIAT Balilla of 1934. The drawing shows a longitudinal cross section; the rear of the gearbox has a sliding train for the first, second and reverse speeds; the front features synchro-mesh gears for the third and fourth speeds (from Genta Morello 2009)

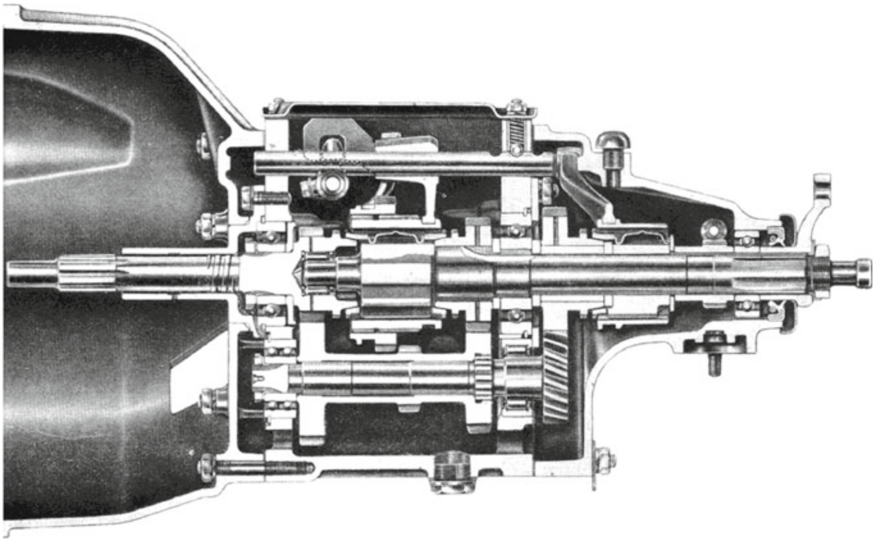

Fig. 4.44 Four speed gearbox of FIAT 1400 of 1950, with full synchronization, except for the first gear. The reverse speed is obtained through a sliding idler, not shown in this figure (from Genta and Morello 2009)

4.3.2 Friction Clutch

In the earliest cars, belt transmissions integrated the start-up function into the device used to change speed, but this was not the case in gearboxes, where a dedicated mech-

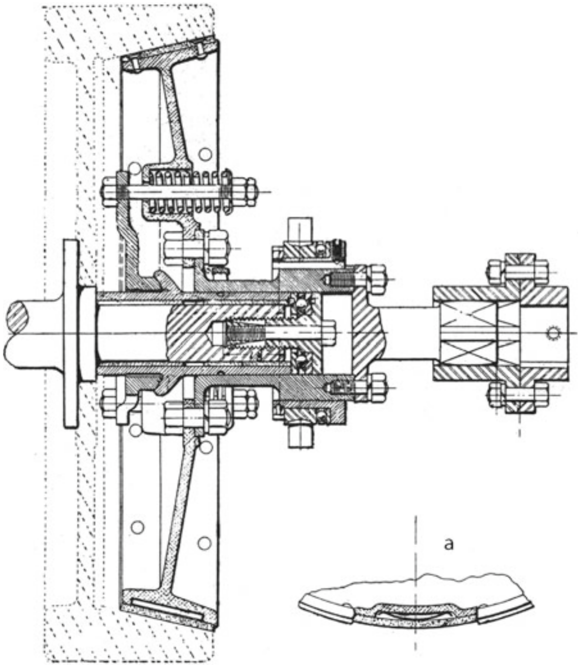

Fig. 4.45 Bevel clutch with leather linings. Clutch conicity (1:2) is limited by the available friction coefficient to avoid irreversible sticking (redrawn from Genta and Morello 2009)

anism was needed. This mechanism, a friction clutch, or, simply *clutch,* posed designers many problems related with its operating life. As already seen, bevel clutches were used since the beginning of the automobile era.

An example of bevel clutch of the first years of the past century is shown in Fig. 4.45. The friction surface was covered by a leather lining, riveted on a bevel pulley of cast iron. Although the famous synthetic material called Ferodo® had been invented by Frood in 1897, it became widely applied only in the 1920s. Leather had a friction coefficient similar to that of modern materials, but offered a limited performance in terms of heat dissipation and duration, requiring active surfaces having a large area. On the other hand, leather was, at those times, cheap and easily repaired or replaced.

In this application there was a single active surface shaped like a cone, a geometry that was chosen to limit the disengagement force on the pedal, which depended upon the cone diameter and engine torque. Due to the difficulty of integrating the leather lining into its support disc, the active surface was usually single rather than double, as it is in modern clutches.

With reference to the previous figure, the engine flywheel features a short shaft, bearing the reaction structure of the load springs working on the friction surfaces. Many coil springs (only one is shown in the cross section) pushed the tapered friction

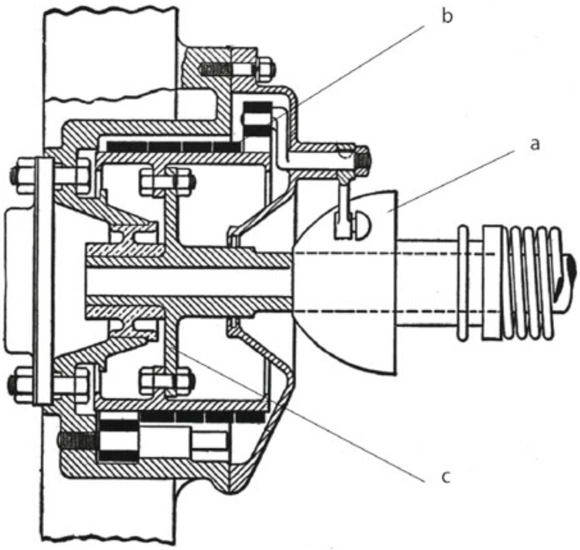

Fig. 4.46 Spiral spring clutch. The clutch pedal moves the ogive *a* that closes the spring *b* onto the input shaft *c*, creating a friction force; the same force increases the spring tensile force (redrawn from Genta and Morello 2009)

disc against the flywheel. The leather lining was riveted on this disc; very thin leaf springs (see detail *a*) were set between the lining and the disc to make the engagement more progressive.

With this kind of architecture, the gearbox input shaft must be able to slide on a square counterpart. Friction conicity (1:2 on this drawing) was limited by the friction coefficient between leather and iron, to prevent irreversible sticking of the clutch after engagement.

The large engine displacement of many cars and the limited size of the flywheel made many clutches too heavy to be operated; for this reason other mechanisms were also developed. The idea was to exploit the mechanical property of wound linings to reduce working forces. Here the friction force is itself used to increase contact pressure, as in leading shoes of drum brakes. This principle was applied through band clutches.

An application of this principle is shown in Fig. 4.46; a coil spring with rectangular cross section and with the coils quite close to each other (*b*) is installed in a cavity in the flywheel. One end of the spring is fixed directly to the flywheel, through the eye in the lower part of the figure; the other end is connected through a rocker arm.

If an ogival body *a* is moved closer to the rocker arm, the spring is twisted and its internal diameter is reduced. The gearbox input shaft *c* is surrounded by the spring with a small clearance so that when the ogive is advanced through the clutch pedal the spring closes on the shaft with a resulting friction torque.

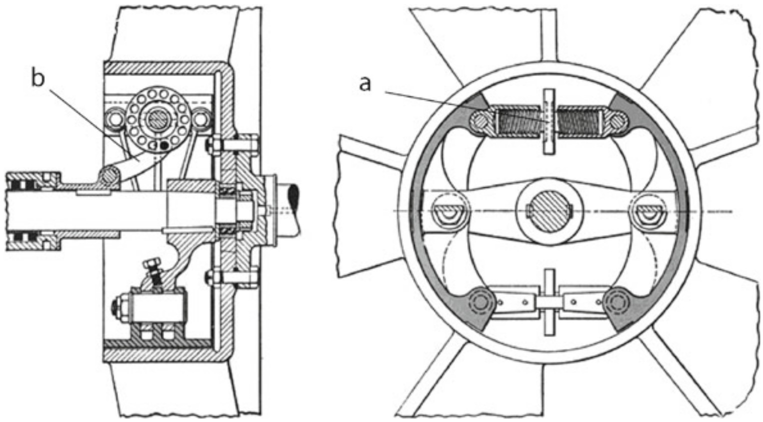

Fig. 4.47 Radial shoes clutch. The shoe displacement is caused by a screw mechanism *a*, operated by the clutch pedal through a crank *b* (from Genta and Morello 2009)

The friction tensile force along the spring coil increases the tangential force toward the spring eye, without increasing its reaction on the rocker arm; the resulting friction torque is an exponential function of the winding angle, which can be increased indefinitely. With a modest friction coefficient between metals it is possible to transmit the desired torque with a reasonable force on the pedal; the drawback is the roughness of the engagement maneuver, only partly eased by the spring elasticity.

A very different configuration based on the same principle is shown in Fig. 4.47; the torque is transmitted, in this case, by two shoes that expand in a drum, as in a drum brake. The shoe motion is created by a screw *a* that is moved by a crank and rod mechanism *b*; the disc shape of the crank is chosen to allow a simple play adjustment, to compensate for lining wear.

Faced with a difficult problem, inventors investigated many different solutions before consolidating and improving the best one; to solve these problems electric and hydrostatic transmissions were also investigated and applied.

The final solution was consolidated in the 1930s with the single disc clutch with synthetic friction linings; one example from this period is shown in Fig. 4.48. The friction surface is now flat and double, so that it is possible to transmit a double torque with the same force. The friction disc is mounted within two surfaces (the flywheel and the pressure disc) that are compressed by a number of coil springs against each other; a set of levers *a* on the pressure disc are used to release the clutch with the axial motion of a thrust bearing *b*.

This kind of clutch received its last improvement by the application of disc springs; these were introduced at the end of the 1970s and allowed many advantages, such as a further reduction of pedal force and a general simplification of the mechanism.

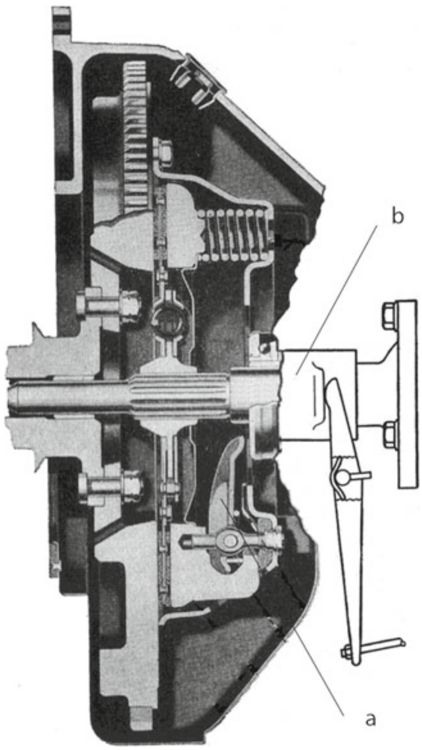

Fig. 4.48 Dry single disc clutch with coil pressure springs. A set of release levers *a* articulated on the pressure plate is used to disengage the clutch, through the displacement of the throwout bearing *b* (redrawn from Genta and Morello 2009)

4.3.3 Automatic Gearbox

Automatic gearboxes had their own history, one that received a crucial contribution from the American automotive industry. This is not to suggest that Europe failed to contribute to this development; many fundamental inventions in this area were actually developed on this continent, but nevertheless the European market, smaller and more fragmented, did not justify the mass production of this gearbox until recently.

The problems to be solved in developing an automatic gearbox included a different mechanism for engaging gears and starting the vehicle, easier to operate with the available automatic controls. These could be mechanical (exploiting centrifugal forces) or hydraulic (exploiting the pressure variation of the oil in a rotary pump).

Today this problem appears in a new context, because electronic microprocessors allow also an easy automatization of synchronizers and friction clutches, in use on manual gearboxes; many existing vehicles already substantiate this statement.

The first step was the development of gearboxes where speed shifts were possible without dangers to gear wheels and other parts that had to be synchronized. From this point of view the single stage, two speeds, manual gearbox of De Dion-Bouton, developed at the beginning of the past century and shown in Fig. 4.49 can be consid-

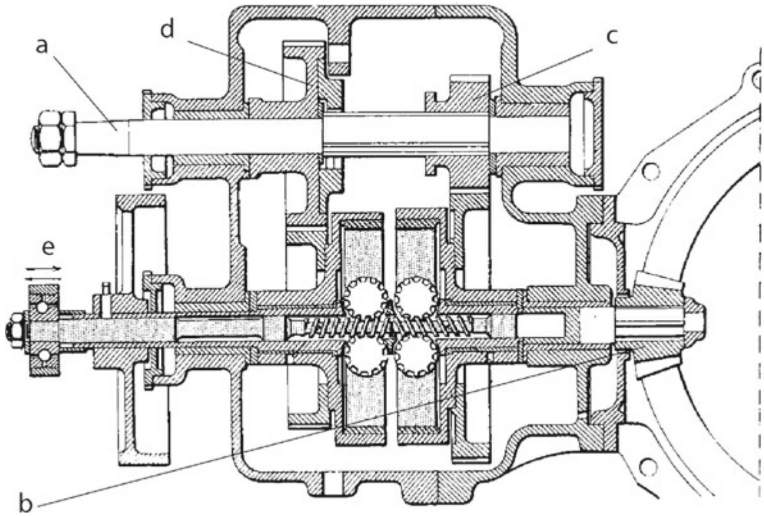

Fig. 4.49 The De Dion & Bouton gearbox can be considered as a precursor to power-shift gearboxes. By shifting a shaft with the bearing *e*, it is possible to engage one of the two shoe clutches available on each gear; a start-up clutch is not required (redrawn from Genta and Morello 2009)

ered as a precursor of automatic transmissions. In the figure the input shaft *a* and the output shaft *b*, which moves through a bevel gear the pinions of the chain drive are shown. The two driving gears *c* and *d* always mesh with the driven wheels idling on the output shaft. The engagement of the wheels is made by shoe clutches, similar to those already discussed in Fig. 4.47, controlled by screws.

By shifting the shaft with the thrust bearing *e*, it is possible to engage one clutch and to disengage the other one. As a consequence, a start up clutch needs not to be used during gear shifts. Although developed for manual gearboxes only, this kind of clutch is a relevant precursor of the powershift gearbox with band brakes and multi-disc clutches.

A second gearbox of historical relevance is that of the Ford Model T of 1908, the first car to be produced by the millions. This gearbox; based on planetary gears instead of ordinary gears, is shown in Fig. 4.50.

Planetary gears had not been invented by Ford, since they were already used in other applications. They may have been invented by Bodmer in 1834, although there is evidence that these mechanisms were already known to the ancient Greeks for devices used in performing astronomical computations. The three satellites v, r^1 and r^2 (the unusual position for the subscript, not to be confused with an exponent, is taken from an original figure), rotating on a single carrier, fixed to the engine flywheel are clearly shown in Fig. 4.50. They mesh with the corresponding sun gears s, s^1 and s^2. If the sun gear s is locked, by rotating the flywheel and the carrier a reduced output speed in the opposite direction is obtained at the sun gear s^2, fixed to the output shaft.

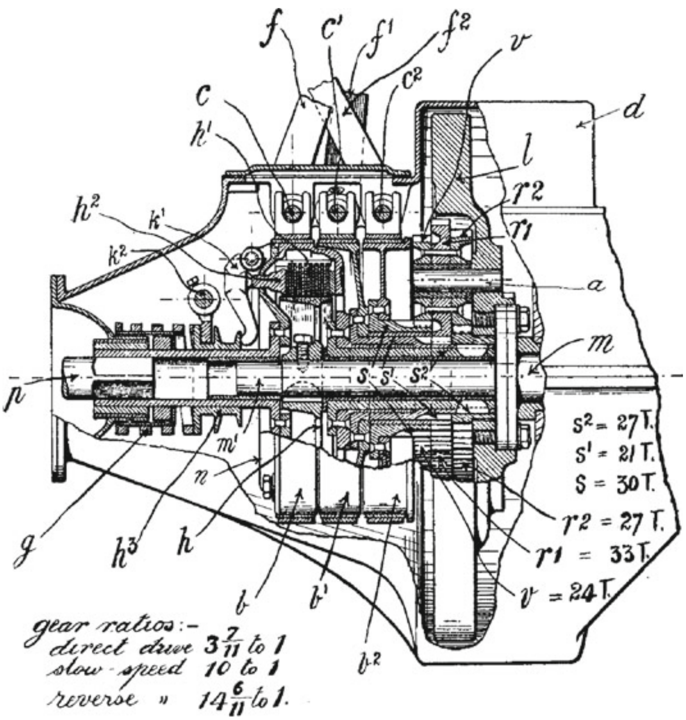

Fig. 4.50 Gearbox of Ford model T of 1908 based on planetary gears. One reverse gear, one reduced forward speed and a direct drive are available (from Genta and Morello 2009)

On the other hand, by keeping the sun s^1 locked, a reduced speed in the same direction, again at the sun s^2 ensues. A note in the figure reports the transmission ratios that were obtained, including the transmission ratio at the differential.

If the multi-disc clutch h^1 is engaged by shifting the sleeve h^3, it is possible to put the gearbox in direct drive by locking the hub h, rotating with the crankshaft, with the output shaft.

To obtain the different states of the gearbox, the sun gears rotate with the drums c, c^1 and c^2, which can gradually be stopped using the band brakes that are in turn controlled by front cams, moved by pedals. The lower part of these pedals is shown in the figure with the letters f, f^1 and f^2. The pedals have a spring system that locks them in either the released or depressed position: each pedal raises when another is depressed.

When engine and car are both stopped, the pedal f must be depressed so that the clutch h is engaged and the vehicle is in parking condition. By releasing the clutch h, through a lever, the engine is disengaged and can be cranked. The car is still braked. By depressing one of the pedals f^1 or f^2, the pedal f is raised, the car is left free to move and will start-up in low gear, either forwards or backwards: The vehicle can be put in reverse even when the vehicle is moving, and start-up on slopes is made easier.

The pedal f^1 can be released, as soon as the suitable speed is reached, by engaging the clutch h. The car is now in direct drive.

The gearbox is controlled by driver actions, but clutch management is performed automatically during gear shifts. The way to obtain a fully automatic gearbox from this situation was still long, but these achievements brought the final result closer. The configuration of this gearbox allows us to understand why planetary gears were preferred to ordinary ones in automatic transmissions: The main reason was the ease of integrating brakes and clutches.

A further step was made in 1928 by Wilson in England, who proposed a gearbox with two planetary gear trains in series, with the carrier of the first gear connected to the ring gear of the following one. With two planetary gears it is possible to obtain three speeds forward, one of them being a direct drive, and a reverse speed.

These gearboxes, similar in use to those of the Model T, were semi-automatic with manual preselection; according to this concept, a small lever close to the steering wheel was used to select in advance the next gear to be used. At this point no gearshift could yet start, but the brake mechanisms were arranged for the gearshift to be eventually made, as soon as the driver depressed a pedal specifically provided for this purpose. This last pedal was located where the clutch pedal normally is positioned.

With this mechanism the driver was helped in performing a coordinated maneuver of the gear stick and clutch; although the energy needed for gear shifting was still produced by driver's muscles through a pedal.

A particularly advanced semi-automatic gearbox was introduced by Cotal in 1934, in France. This gearbox, whose cross section is shown in Fig. 4.51, includes three planetary gears. In the figure the engine is on the left, the output shaft on the right. In this gearbox the brakes are substituted by toroidal electromagnets, used to lock some selected elements of the gear train. The first electromagnet puts the corresponding gear set into direct drive, by locking the sun and ring gears together; the second one is used to obtain a reduced speed, while the third, located at the right, to obtain a faster speed. The last electromagnet is used to set the gearbox in direct drive.

By energizing electromagnets in combination, two reduced speeds, a direct drive and an overdrive can be obtained. A small switch with five positions, located close to the steering wheel, allowed the four gear ratios to be obtained automatically, without the use of clutches, whose function was controlled by the timing of the electromagnets and the inertia of the parts to be accelerated or slowed down during shifts. The remaining fifth position of the switch was used for putting the gearbox into idle, with all electromagnet circuits open.

The first planetary gear a is operated, instead, manually, when the car is not moving and the transmission is in idle position; a control lever moves the carrier back and forth, to engage with the ring gear, obtaining a forward speed. If the carrier is locked a reverse gear is obtained. Vehicle motion can be obtained, after this manual shift, with the first gear, controlled by its electromagnet. The most relevant drawback of this gearbox were its heavy weight and large size.

Semi-automatic Wilson and Cotal gearboxes were used primarily by European manufacturers specializing in luxury cars; the World War Two crisis caused many of

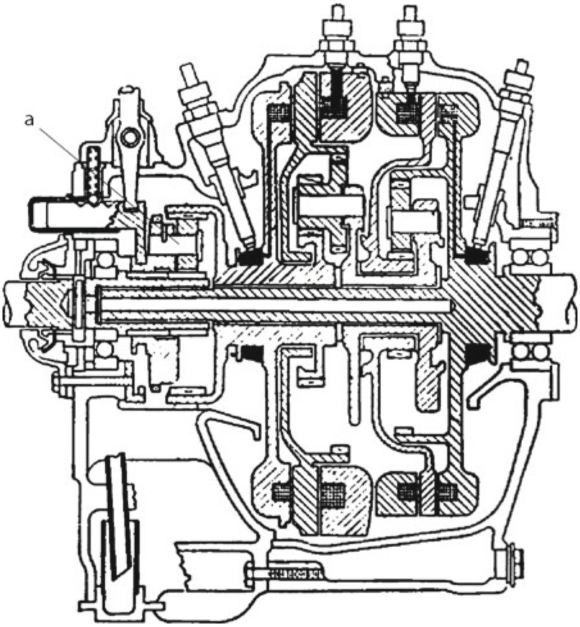

Fig. 4.51 Semi-automatic gearbox produced by Cotal starting from 1934. The different elements of planetary gears are braked by electromagnets. The reverse gear is engaged manually (from Genta and Morello 2009)

these manufacturers to disappear, and these transmissions disappeared together with them.

The final step toward modern automatic gearboxes was taken by using hydraulic torque converters. A torque converter had been introduced by the German shipbuilding industry, after the invention of Föttinger in 1905, well before their application in cars. He patented a torque transmission system connecting in the same hydraulic circuit a centrifugal pump and a turbine. With this device, the torque transmission is obtained by the momentum variation of the flow through the rotating blades, and is possible even when the pump, connected to the engine, is rotating and the turbine, connected with the vehicle wheels, is stationary.

The idea was developed further through the design of an integrated device of reduced size, that was almost interchangeable with the conventional friction clutch. In 1910, a patent for a hydraulic clutch, simplified by the elimination of the stator, was filed.

Again in Germany, in 1928, the research consortium Trilok developed a torque converter, that integrates the performance of the torque converter and the hydraulic clutch in a single machine. This was done by mounting the stator (that actually now is no more restrained from rotating) with a freewheel.

The first automotive automatic gearbox was produced by GM; called the Hydramatic, it has been in production since 1939: A cross section of this gearbox is shown

in Fig. 4.52, where the hydraulic clutch *a*, followed by two planetary gear trains *b*, able to obtain three forward speeds and a reverse speed can be seen. The gears are engaged and disengaged by two band brakes *c* and two multi-disc wet clutches *d*.

Brakes and clutches are operated by oil pressure, generated by a gear pump, and modulated both by servo valves and a manual control located on the steering wheel. Gear shift automatization is based upon the comparison of the oil pressure generated by this first pump (dependent on engine speed) with the pressure generated by a second pump driven by the transmission output shaft (dependent on vehicle speed). The difference between these two pressures is used to move the gear shift servo valve. This valve is also made sensitive to the accelerator pedal position through a spring loaded mechanical link.

This system worked quite well on level road, with upshifting occurring at higher vehicle speeds when the accelerator pedal was more depressed; but on slopes or on winding roads the automatic control had to be corrected by the manual selector. The hydraulic clutch is always transmitting the engine torque and was used both for starting the vehicle and to damp out driveline torque vibrations.

The bulk of these gearboxes was absorbed by war production; their application to commercial cars began only in 1946 and was much appreciated by the public.

The Dynaflow gearbox, also from GM, has been produced since 1948. It introduced many improvements over the previous model. The planetary Wilson gear train, much simpler, allowed three forward and a reverse speed to be obtained, with two band brakes and a multi-disc clutch used in combination.

The most relevant step forward was the introduction of an improved torque converter, featuring a two stage reactor on freewheels; with this device it was possible to start-up the car with a torque transmission ratio greater than two (instead of one, by definition the ratio on the hydraulic clutch), allowing in the meantime the torque converter to work as a clutch, obtaining a better efficiency when input and output torques of the converter were equal.

This layout is still present in automatic gearboxes, even if the need for a higher number of transmission ratios justified the application of additional planetary gear trains.

The Gyromatic gearbox designed in 1949 by the Dodge Division of Chrysler is also worth mentioning for its original features. The clutch of this gearbox, that includes a hydraulic clutch and friction clutch operated by a pedal in series, is shown in Fig. 4.53. Some gear shifts always demanded operating a pedal clutch, but they were rare, thanks to a particular automatization device.

The twin friction and hydraulic clutches allow damping transmission vibration and a smooth start-up, even if the pedal is released without particular skill; in addition, the car can be kept stopped on a slope simply through the use of the accelerator pedal. The following start-up is considerably easier. Similar twin clutches were also applied in combination with conventional manual gearboxes on some European cars in the 1950s.

A clutch of this kind could be used in connection with conventional manual gearboxes where the clutch disengagement was made electrically, by simply touching the gear stick.

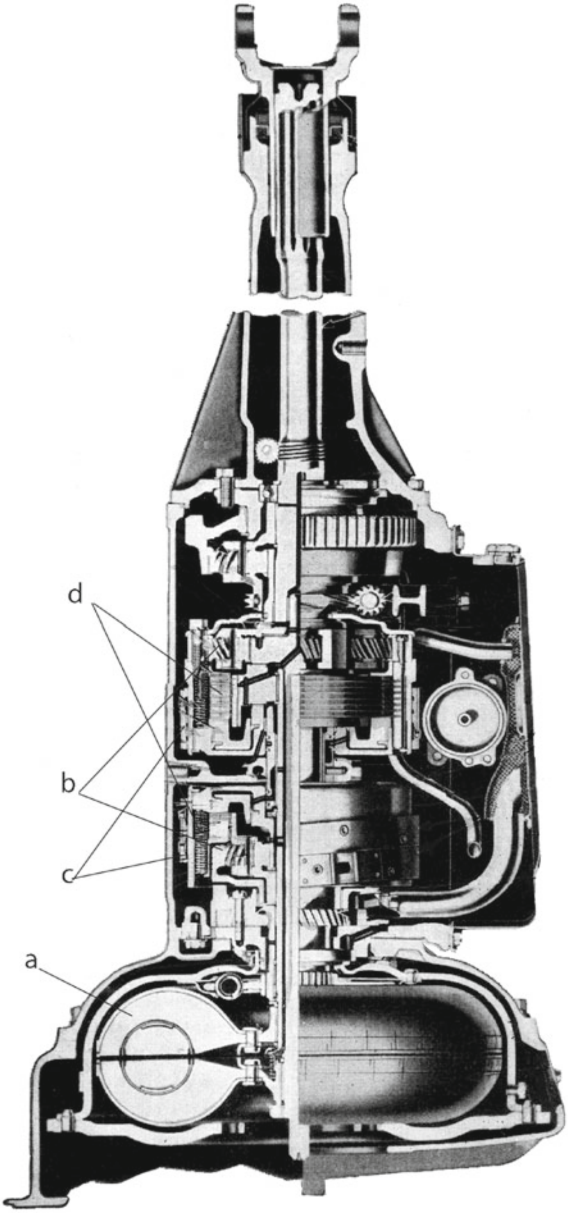

Fig. 4.52 GM Hydramatic transmission. The hydraulic clutch *a*, followed by three planetary gear trains *b*, able to obtain three forward and a reverse speed, can be seen (redrawn from Genta and Morello 2009)

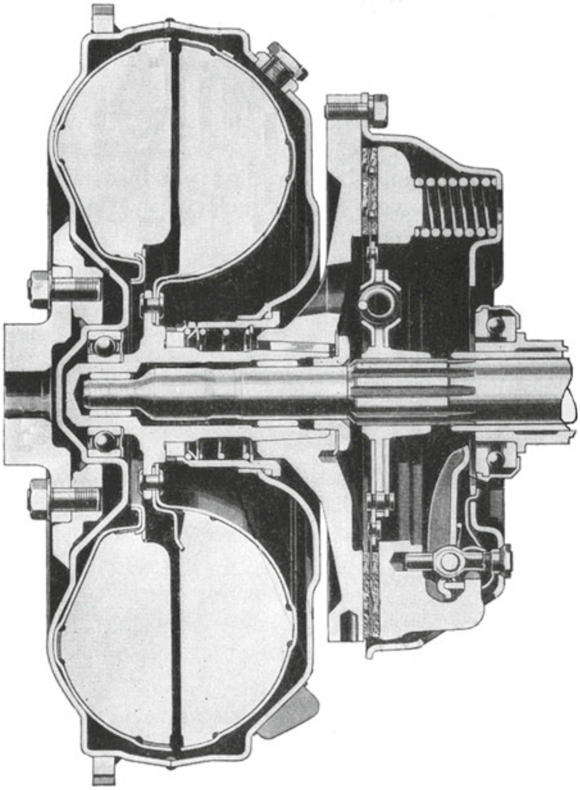

Fig. 4.53 Hydraulic clutch of the Gyromatic semi-automatic gearbox, produced since 1949 by Dodge. It is also provided with a conventional friction clutch with pedal control (redrawn from Genta and Morello 2009)

A particular European contribution to automatic gearbox development, the Variomatic transmission, was introduced by DAF Daffodil in 1950. This was probably the first reliable application of the continuously variable transmission to a car. This transmission, suitable for front engine, rear-wheels drive cars, is shown in Fig. 4.54. The engine drove two variable diameter (expandable) steel pulleys through a transmission shaft and a differential. These pulleys drove similar pulleys connected to the driving wheels through a special rubber belt.

The sides of the driven pulleys were compressed by coil springs that guaranteed the correct friction with a rubber belt; the sides of the driving pulleys were, instead, compressed by centrifugal masses and engine manifold pressure. Through this device the speed ratio variation took into account engine speed and required torque. A centrifugal friction clutch made car start-up completely automatic.

This transmission received no further application because of its strong impact on the vehicle architecture.

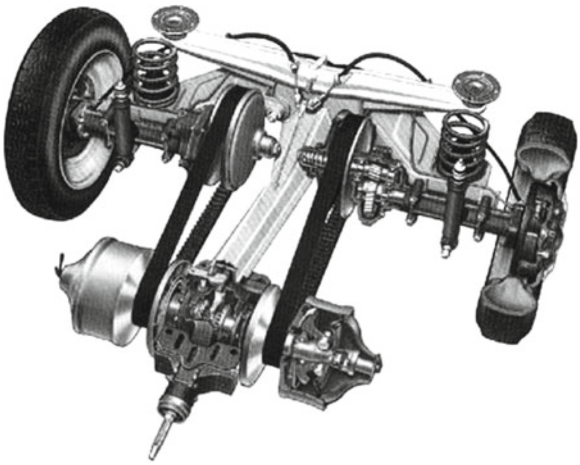

Fig. 4.54 Automatic Variomatic transmission of the DAF Daffodil of 1950. It is made of expandable pulleys and rubber belts, reinforced by cords (from Genta and Morello 2009)

The concept was completely reworked by Van Doorne (the DAF holding company), introducing a completely new design. This study had as its objective the development of a steel belt variable transmission of reduced size, capable of being interchanged with conventional manual gearboxes. An experimental application was made by Fiat and Ford and was followed later by mass production. This kind of automatic gearbox has now seen a number of applications on cars of different brands.

4.4 Alternative Powertrains

Propulsion systems different from internal combustion engines were considered at the beginning of automobile history; in particular steam engines have been on the market since the end of the eighteenth century, while electric cars since the 1880s, about ten years earlier than the first gasoline automobile. Both were mainly used in much heavier vehicles.

This situation was justified not only because internal combustion engines were still in their initial development stage, but also because there were technical reasons to believe that this kind of engine was unsuitable to vehicles.

Consider an engineer from the end of the nineteenth century, making a decision about the powertrain to be installed in the vehicle he is designing. At that time, internal combustion engines fuelled by gas with the related fuel tank had a mass and a bulk that were not smaller than that of alternative solutions, and the reduced clearances needed for their correct operation, that were affected by a wide range of operation temperatures, introduced severe design complications. These difficulties

were mitigated only after carburetors were introduced by Daimler and Benz, allowing the use of liquid fuels, having a better energy density.

A second issue, difficult to be solved, was the need to apply a *torque converter* (gearbox and clutch) to adapt the engine torque to the traction requirements of the vehicle. From the first automobile magazines it is clear that the correct combined use of clutch, gearbox and accelerator controls was a major concern for early drivers and engine cranking practically made driving impossible to women. None of these problems were present in vehicles powered by electric motors or steam engines.

There was a further point in favour of electric motors: the maximum available power, particularly important in race applications, was higher.

Until the first years of the twentieth century, foundry and machining technologies allowed production of small displacement engines only, with no more than two cylinders. On the other side, considering feasible values for the top engine speed, a power of 20 HP, suitable to reach, with a heavier vehicle, a performance comparable with a horse driven carriage, could be obtained only with a displacement of at least 4 l. This goal could be achieved only with 4 or 6 cylinders engines, that were put in production between 1903 and 1905.

Electric or steam engines of that time could already reach this goal and they were consequently chosen for heavy and fast vehicles: trucks, buses, taxis and vehicles designed to achieve speed records were powered by engines of this kind. The first vehicle to reach a speed of 100 km/h, setting a new world record in 1899, was the electric vehicle Jamais Contente designed by Camille Jenatzy. This record remained unbeaten till 1902 when Leon Serpollet (driver and car manufacturer) reached 120 km/h with a vehicle powered by a steam engine. At the end of the same year, this barrier was broken by a vehicle powered by an internal combustion engine, but the second major milestone of 200 km/h was again reached by a Stanley Steamer in 1906.

This date marks perhaps the end of the golden age of steam engines, followed a few years later by the decline of electric motors.

4.4.1 Electric Cars

The fame of the *Jamais Contente* (in English, Never Satisfied) by Camille Jenatzy is linked with the early attempts to break the 100 km/h barrier with a road vehicle.

The history of electric vehicles started earlier, with Charles Jeantaud, one of the most important car manufacturers in France, operating between 1881 and 1906 in Paris. He inherited his shop from his father, a famous coach builder; and developed at least two important inventions: the electric car and the steering mechanism for solid axles, according to Ackermann's rule. There is a relationship between these two inventions.

The most important share of the Jeantaud's production were the so-called *fiacres,* the taxis for the city of Paris. A similar vehicle is shown in Fig. 4.55. The reasons for choosing this layout for one of the first self-propelled vehicles is unknown, but a

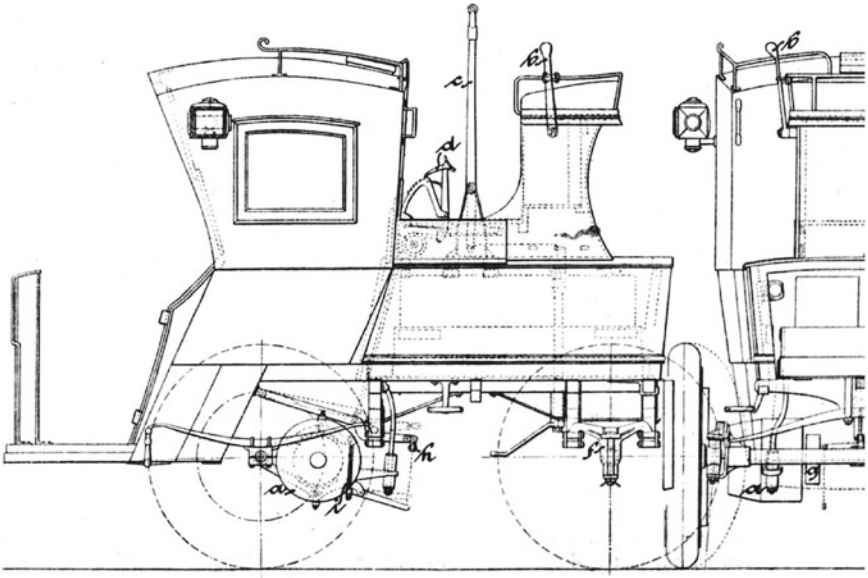

Fig. 4.55 One of the electric Fiacres of Paris (From Dinglers Politechnischer Journal 1898)

reasonable guess was that Jeantaud based his design on similar horse-driven vehicles. Horse-driven Fiacres had passenger seating in the front row, for a good visibility of the road while the driver was seated on top of the vehicle to effectively supervise the surrounding area.

The choice of front wheel drive was likely dictated by the analogy with horse driven carts: Like a horse was pulling the cart and steering the vehicle, the motor was expected to perform the same functions and thus placed on the front axle. Figure 4.56 shows how Jeantaud designed the front driving and steering axle, with a king-pin steering mechanism and a bevel gears transmission able to drive the steering wheels.

Jeantaud was one of the first to realize the potential of sport events to increase the visibility of his new invention and related sales. In 1898 an electric Jeantaud car, driven by Gaston De Chasseloup Laubat powered by a 35 HP electric motor reached a top speed of about 63 km/h, setting a world speed record for cars. The fact that the record was obtained by a car must be stressed, since an earlier record was reached by a bicycle, with 67 km/h, and rail vehicles had already broken the barrier of 100 km/h.

Camille Jenatzy was the ideal challenger for Chasseloup because he was both his rival in other sports and a competitor of Jeantaud, with his Compagnie Internationale des Transport de Paris, producing and managing a fleet of electric Fiacres. Jenatzy was also one of the first manufacturers of rubber products in France and, because of this, probably had the chance to meet the Michelin Brothers.

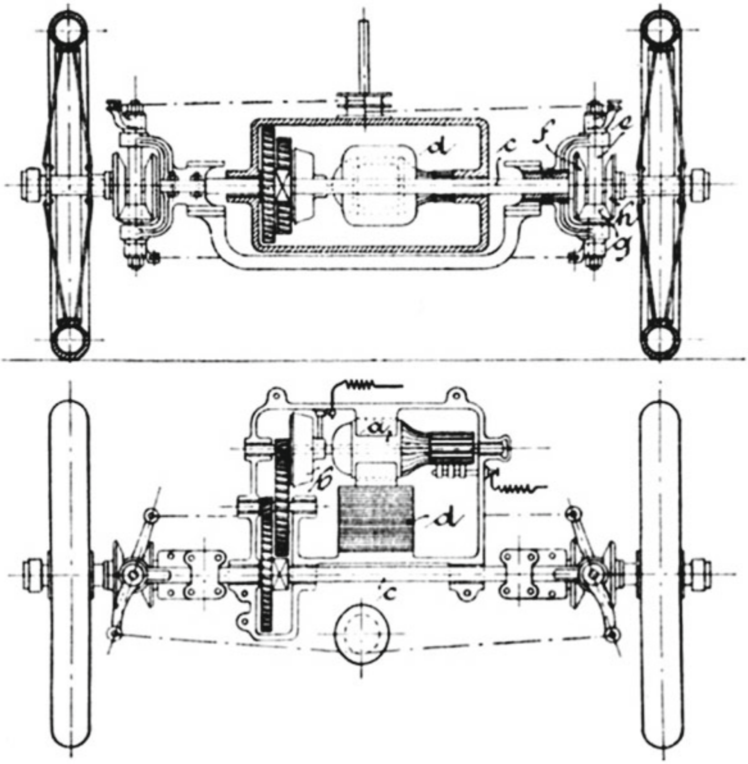

Fig. 4.56 Front and top view of thedriving and steering front axle of a Jeantaud Fiacre (From Dinglers Politechnischer Journal 1899)

To challenge Chasseloup he modified one of his electric vehicles, powered by a 68 HP electric motor and adapted a set of wheels to the new Michelin pneumatic tires. Road tests started in January 1899 and, after three different tests followed by design improvements, Chasseloup was still the winner with 92 km/h. Jenatzy did not give up, introducing in his car a streamlined body, made with light weight aluminum alloy and a larger set of lead-acid batteries.

In April 1899 the car, shown in Fig. 4.57, was timed at about 106 km/h. This record remained unbeaten for a while. The threshold of 100 km/h was considered to be critical, because of alleged breathing difficulties and because human reactions were thought to be too slow to operate the controls at this speed.

The Jamais Contente may be impressive to us for the naiveté of some details, but embodies some deeply innovative ideas. The body shell is in fact shaped as a slender body, with an elliptical cross section: It is probably the first car where a particular design effort was aimed to reduce aerodynamic drag. Its shape is very different from that of early automobiles, which maintained the basic body of a horse driven carriage with just some rough shield around the engine and the chassis subsystems added.

Fig. 4.57 A full scale replica of the1899 electric vehicle Jamais Contente, the first car to break the barrier of 100 km/h (picture of a replica, presented at Rétromobile, Paris, 2009)

The misunderstanding of some aerodynamic features, like the pointed nose, were common to the early airships and aircraft fuselages.

A second important point about the body is that it is made by curved light alloy panels joined by rivets, like airplane fuselages of much more modern times. This alloy was developed and patented for this application, with the commercial name of *partinium*, an aluminum alloy with copper and zinc. The chassis was, on the contrary, traditional, bearing some similarity to that of a production Fiacre. Anyway, it represents the state of the art of the time and was made with steel beams with iron suspension joints.

Suspensions were made by two rigid axles with semi elliptical leaf springs; rear springs were doubled to support the weight of the electric motors and batteries. The rear axle was obtained from a riveted steel plate structure including the two electric motors and the wheel hubs. The motors thus were located on the unsprung mass. Wheels were wooden artillery wheels, but had pneumatic tires. The contribution of tires to reduction of the rolling resistance on macadam roads was impressive and represented one of the most advanced characteristics of this car.

The energy storage system included 100 lead-acid batteries made by Fulmen, generating a voltage of about 200 V and the short circuit current reached 250 A. The rated power thus reached 50 kW (about 68 HP) without taking into account electrical and mechanical losses which were at any rate low due to the use of two electric motors with separate excitation, each driving one of the rear wheels directly, without gearbox and differential.

A pedal combination switch allowed to connect rotary and fixed windings in series and parallel with a total of six combinations of voltage-current characteristic, so that it was possible to accelerate the vehicle almost always at rated power without a gearbox. Many electric cars with similar technical features but lower performance were sold by different manufacturers in this period of time.

Electric cars were more popular in the United States than in Europe, because of specific factors, like a more intense use in urban environment and the existence of many women interested in driving a car: As already said, the mentioned complications of internal combustion engines discouraged women from driving. The most famous

Fig. 4.58 Pope Model 1901; note the electric motor integral with the rear axle (National Automobile Museum of Torino)

manufacturers were Pope, Studebaker, Detroit Electric, Baker, Rauch & Lang. The 1901 Pope, shown in Fig. 4.58, may be an example of a two seater cheap electric car.

Also in this car the electric motor was unsprung, directly acting on the rear axle, but through a couple of gears to reduce the size of the motor. Regulation was again performed using a combination switch.

An example of luxury city car may be the nice 1911 Rauch & Lang Brougham, shown in Fig. 4.59. It appears that this car inspired Walt Disney in designing the famous Grandma Duck's car. Its technology is the same as in previous models but its body suggests its popularity among women customers; front seats can turn to look ahead or behind, to favor conversation with the rear sitting driver and trimming is particularly refined and elegant.

The decline of electric cars started in 1912, at least in the United States, when electric starters began to be applied to internal combustion engines, solving one of the most important negative aspects of start-up. No relevant technical improvements able to make electric cars competitive with internal combustion engine cars, except in very particular situations, were introduced until the beginning of the twenty-first century, when Lithium batteries appeared on the market.

Fig. 4.59 The 1911 Rauch and Lang Brougham is an exampleof an electric luxury city car that may have inspired Walt Disney in designing the famous Grandma Duck's car (Auto Museum of Sacramento)

4.4.2 Steam Cars

Before discussing in details some important steam cars it must be stated that the most critical issue of this propulsion system has always been the time needed to pressurize the boiler, since all the water in the boiler had to be heated before having some steam available for propulsion. A second major issue was water consumption, because the expanded steam was directly exhausted to the environment. However, water consumption was not higher than that of cars powered by internal combustion engines, because in the early cars of the latter type the consumption of cooling water was higher than fuel consumption by a factor of ten.

The attempt to solve these two problems was the driving force behind the development of steam cars during the about 30 years in which they were built.

The steam car built by Enrico Pecori in 1891 (Fig. 4.60) is emblematic of other contemporary cars made by Serpollet, De Dion-Bouton and Olds; the choice of speaking of this car to describe the initial state of the art in this technology is motivated by the excellent conservation state of this old car.

The mechanical layout is based on a vertical boiler located in front of the driver's seat, as can be seen in the figure, so that the driver could feed the furnace and the rear driving axle could carry most of the load. The chassis was made according to bicycle technology of that time, with tubular beams and radial spoke wheels with solid rubber tires. Moreover, the car had no suspensions.

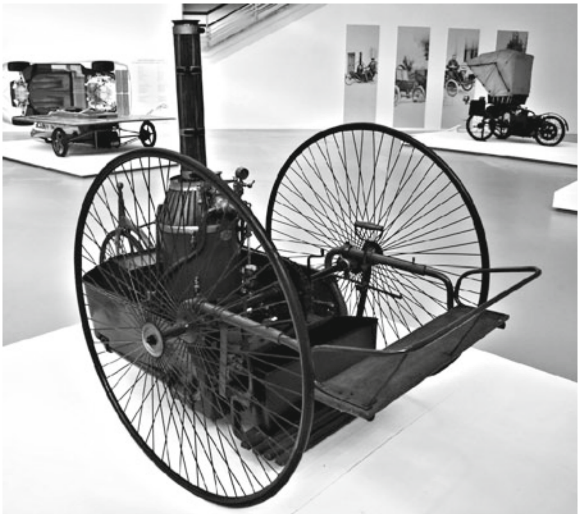

Fig. 4.60 In the 1891 Pecori steam car the position of the boiler allows the diver to feed the furnace (National Automobile Museum of Torino)

Controls were unusual, if compared with the current praxis: A handle at the right of the driver was turned to steer the front wheel, while a small crank in front of the driver could apply a band brake on the differential.

The Cornish boiler, like other boilers of this kind, was made by a vertical water tank surrounding the furnace which was fed through a front door and exhausted the smoke though a central chimney. This kind of boiler was not completely filled with water, because its upper part was used to store the steam under pressure. A solid fuel (wood or coal) was introduced through the furnace door as soon as the steam pressure was too low. Steam was stored in the boiler, so that the timing of fuel introduction was not critical. Boiler, chimney and cylinders were lined by wooden slats, to protect the driver from burns and to limit heat waste to the outside.

Steam pressure, proportional to the torque potentially available for traction, was monitored through a pressure gauge, while actual working pressure was regulated by turning the tap in front of the driver. Opening this tap gave the vehicle an immediate smooth start-up. The warm-up time of a boiler of this kind can be estimated in the range of half an hour.

The steam engine included two horizontal cylinders; one of them is shown in Fig. 4.61 with its sleeve valves on the side. The crankshaft was directly connected to the differential of the rear diving axle through a chain. Many other taps were used to discharge the water condensed in steam piping during stops, to avoid water entering the cylinders, causing severe damage.

Like electric cars, also steam cars were more popular on the American market: In 1902, for instance, the yearly car sale to this country (900 vehicles) comprised 50 % of steam cars, 25 % of electric cars and only 25 % of internal combustion engine cars.

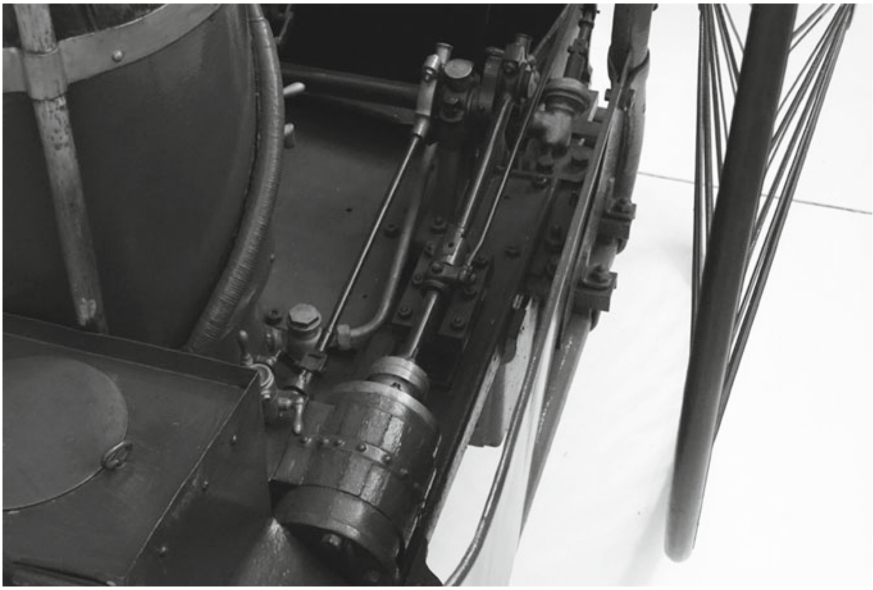

Fig. 4.61 One of the two engine cylinders acting on a transversal crankshaft; this drives directly the differential through a chain (National Automobile Museum of Torino)

The problem of warm-up time was eventually solved by Serpollet in France and by Stanley in the United States, who developed the so-called fast boilers, containing a very small amount of water. The 1904 Stanley Spindle Seat shown in Fig. 4.62 may be used as evidence of the progress made in the 15 years during which steam car technology had constant improvements. The most important were the fast boiler and the distributor regulation shown in Fig. 4.63. The propulsion system was located under the driver's seat.

The boiler is the big vertical cylinder, in the background of Fig. 4.63. It carries many vertical steel tubes that reduce the quantity of water and increase the heat exchange coefficient between water and flames or hot fumes. The fuel was no longer wood or coal, but liquid petroleum distillates and the hot gases no longer heated the boiler by natural draft, but by a more efficient forced ventilation. The heat rate was regulated by the fuel pressure. In this way the boiler warm-up time was reduced to a few minutes.

A detail of a similar engine, featuring two double effect cylinders, is shown in Fig. 4.64. Being a two strokes cycle engine, it offers a driving smoothness that is similar to that of an eight cylinders conventional four strokes cycle engine. The double effect arrangement does not allow joining the connecting rod to the piston directly, as in internal combustion engines, but requires the use of a cross head mechanism.

The engine was directly connected to the rear differential, with no gearbox or clutch between them. The most important difference from the previous example is

Fig. 4.62 The 1904 Stanley Spindle Seat was one of the most popular steam engine cars built in the United States (National Automobile Museum of Torino)

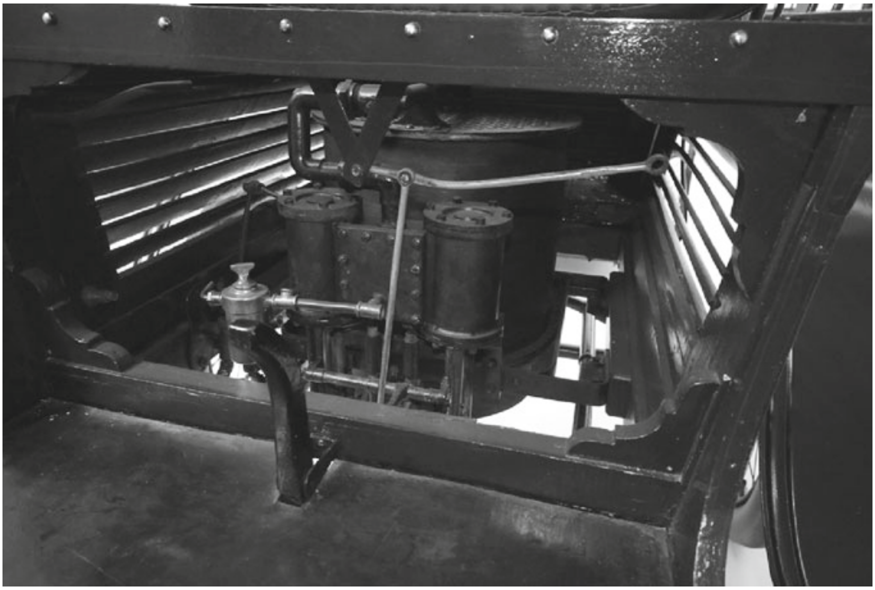

Fig. 4.63 The most important developments in the 1904 Stanley are the fast boiler and the distributor regulation of the propulsion system (National Automobile Museum of Torino)

torque regulation, that was no longer achieved through a choke valve, but by changing the timing of the valves, with reduced energy losses. The intake and the exhaust had a common duct, as shown in Fig. 4.64. A sleeve valve connected these ducts with the

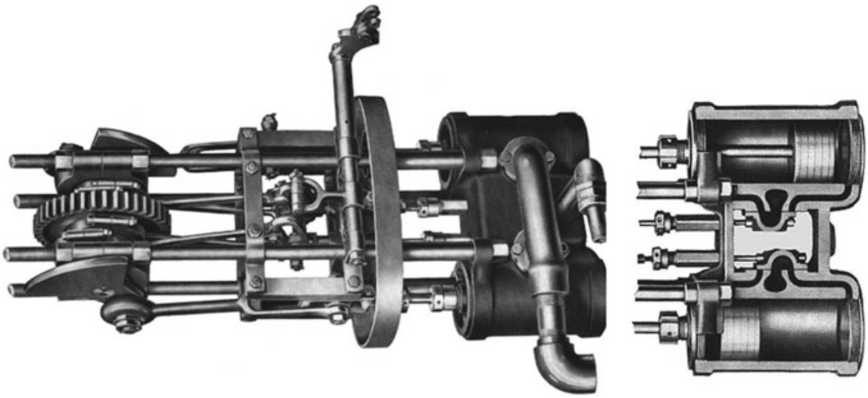

Fig. 4.64 A Stanley double acting two cylinders steam engine; the picture on the right shows the detail of the sleeve valves with adjustable timing (from www.stanleysteamers.com)

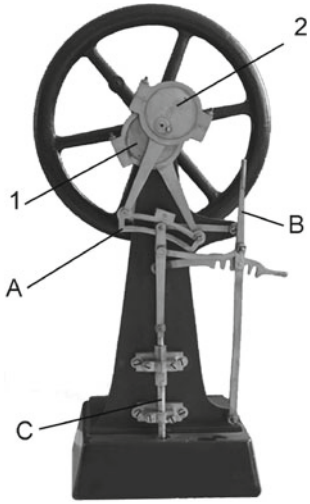

Fig. 4.65 Didactic mock-up of the Stephenson's mechanism used to adjust sleeve valves timing

steam intake (in the center) or, through the exhaust, directly to the atmosphere and the engine torque was regulated by changing the intake retard angle and, symmetrically, the exhaust advance angle. This was performed by changing the sleeve valve stroke.

Figure 4.65 shows a didactic working model of the Stephenson's mechanism used to change the timing of a sleeve valve. The mechanism includes two eccentrics 1 and 2 connected to a link-block A, that moves the sleeve valve C.

A lever B can change the position of the fixed articulation of the link-block. Since the resulting motion of the sleeve valve is a combination of the motion of the eccentrics with opposite phases, any combination can be obtained between maximum direct and reverse torque, including zero torque, when the fixed articulation of the link-plate is coincident with the sleeve valve articulation.

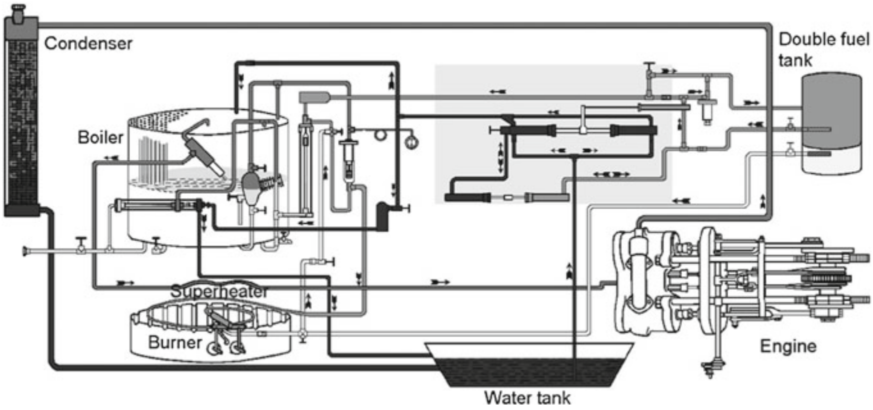

Fig. 4.66 Scheme of steam engine provided with a fast boiler, provided with an additional heater (superheater), close to the hottest area of the burner, and a condenser (redrawn from www.stanleysteamers.com)

A major drawback of this system was exhausting steam to the outside, causing high water consumption, residual heat loss and, not least, an unpleasant fog curtain following the car. All these problems were eliminated by application of a condenser. The scheme in Fig. 4.66 shows the high degree of complexity reached by the latest Stanley engines, at the end of the 1920s.

The fast boiler was provided with an additional heater (*superheater*) located close to the hottest area of the burner, that makes steam available at a pressure of about 40 bar. After expansion, the steam is conveyed to a condenser, similar to, and in the same position as, the cooling radiator of conventional cars. The steam is thus condensed to water (at low pressure) that is then transferred by a pump to the water tank so that water consumption could be limited to the water leaking through the seals.

A further development was related to warm-up speed. Since combustion speed was controlled by the fuel injection pressure, that was in turn generated by steam pressure, manual pumping was the only way to obtain the required pressure at start-up. This problem was solved by using a double fuel tank and by using gasoline for cold starting and then shifting to cheaper kerosene or similar distillates after warm-up. Operating in this way, the greater volatility of gasoline avoided the need of pressurizing the tank when the engine was cold. It is interesting to note that the two fuels were only separated by their density, being contained in the same tank.

As a last remark about steam engines, it may be interesting to recall that some car manufacturers worked on the development of new steam engines at the end of the 1970s. This was due to the fact that the State of California had determined that the main cause of the complex mechanism of atmospheric pollution in the Los Angeles area was the interaction between nitrogen oxides, produced by internal combustion engines, with other pollutants and that, as a consequence, a new law about emission limits was announced. Since at that time no way to reduce nitrogen oxides emission in

internal combustion engines was known, a revival of steam engines seemed to be the best solution. Steam engines could allow both reduction of nitrogen oxides emission (due to the low combustion pressure) and use of alternative fuels, an important goal since an oil crisis was expected because of the depletion of American oil fields. The introduction of three-way catalyst and oxygen sensors made this revival useless only a few years later.